23

THE GEOLOGY OF THE KIEWA AREA

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Abstract

Upper Ordovician sediments were folded and metamorphosed with migmatization on the cores of the main anticlines, during the Benambran Orogeny. Later intrusion of granodiorites took place in the post tectonic intrusive phase of the Bowning Orogeny, and of quartz diorites and lamprophyres in the same phase of the Tabberabberan Orogeny. The early stages of the Kosciusco Uplift were marked by the extrusion of basic lavas.

The dominant fold structure is the Kiewa Anticline, a broad, relatively simple structure, the axis of which has a gentle northerly plunge, and the W. limb of which is sheared through on the West Kiewa Thrust. This thrust, the main fault of the area, forms here, the W. boundary of the metamorphic complex. The structure is dominated by faults and joints, the pattern of which is related to the three Palaeozoic orogenies known to have affected the region. After the Benambran folding, no further folding occurred, with the exception of a fault warp in the Tertiary. Deformation during the post Benambran Palaeozoic orogenies was expressed by fracturing.

The stream pattern, as well as the overall topographic form of the terrain, has been strongly influenced by the faulting, and in particular by the Tertiary fault-warping.

Introduction

The Kiewa area includes the headwaters of the Kiewa, Bundarrah, and Cobungra R., all of which have their sources on the Bogong High Plains. The terrain is extremely rugged, comprising some of the highest parts of the Victorian Alps. Elevation ranges between 1,100 ft at Mt Beauty township, and 6,509 ft on the summit of Mt Bogong. With the exception of the Bogong High Plains, dissection is deep, with the streams actively eroding steep, gorge-like valleys. Weathering of the rocks is advanced, and in general, exposures of fresh rock are restricted to the beds of streams.

The field work, which consisted of regional and very detailed mapping of an area of 300 square miles, together with a large amount of diamond drilling, provided the basic data for the research into the age and relationships of, particularly, the igneous and metamorphic rocks of this sector of the metamorphic complex of NE. Victoria. Petrological studies were essential for this aspect of the project and while earlier workers had studied the petrology of the complex as a whole, very little such work had been attempted for this area.

The most detailed part of the project was the structural research, an aspect of the geology of the Kiewa area which had previously not been examined. Patterns of folding, faulting, jointing and dyke intrusion have been studied. The field work emphasized the importance of structure in the physiographic development of the area, while civil engineering design and construction for the Kiewa Hydroelectric Project emphasized the significance, economically, of structure. Both of these aspects were investigated, the latter in more detail than can be considered in this paper.

This paper is based on part of a thesis for the degree of Doctor of Philosophy in the University of Melbourne. The author desires to express appreciation for the guidance of Professor E. S. Hills. Drs C. M. Tattam, O. P. Singleton, and R. J. W. McLaughlin discussed various aspects with the author, while Dr Tattam read the manuscript. The field work was carried out mainly in the period 1947-1957 when the author was employed by the Geological Survey of Victoria, and the State Electricity Commission of Victoria. It is desired to express appreciation for the inspiration and opportunities provided by Dr D. E. Thomas and Mr G. Paterson. Messrs A. Rufenacht, R. G. Chapman, E. L. Richard, H. H. C. Williams, T. D. Eaton and D. Gibson made possible many aspects of the work. L. F. Huelin and L. J. Clarke served as field assistants. To the author's parents, his wife, and the late Dr W. J. Harris sincere thanks are due for the encouragement given at all times. Assistance to the cost of publication by the University of Melbourne is gratefully acknowledged.

Previous Literature

R. A. F. Murray carried out the first geological survey in the Kiewa area; his main interest was the distribution of the auriferous sub-basaltic gravels, but he claimed recognition of the transition of the Ordovician sediments to metamorphic rocks in the West Kiewa valley. In 1886 von Lendenfeld and Stirling separately explored Mt Bogong from which they recorded material interpreted by them as Pleistocene moraine.

J. W. Gregory (1902) examined the metamorphic boundary at a number of localities, and concluded that this boundary was always faulted. This led to Gregory ascribing a pre-Cambrian age to the metamorphic rocks, a conclusion which Tattam (1929) was unable to substantiate. Tattam's work on the metamorphic rocks showed for the first time that the metamorphism was essentially thermal.

Between 1930 and 1940, J. P. L. Kenny, J. G. Easton, and M. A. Condon carried out preliminary geological investigations for the Kiewa Hydroelectric Project. This work has been described in a number of small reports, both published and unpublished. V. M. Cottle, continuing the work for the Project published a report on the Ruined Castle basalts in 1947.

P. W. Crohn (1949) made a study of the geology of the Omeo district, and extended his rapid surveys to include the E. part of the Kiewa area. Crohn's work included a detailed study of the petrology, as well as a critical review of the physiography of the region. Studies of Tertiary thrusting and of the mylonites of the Kiewa area have been published by the present author (Beavis 1960, 1961).

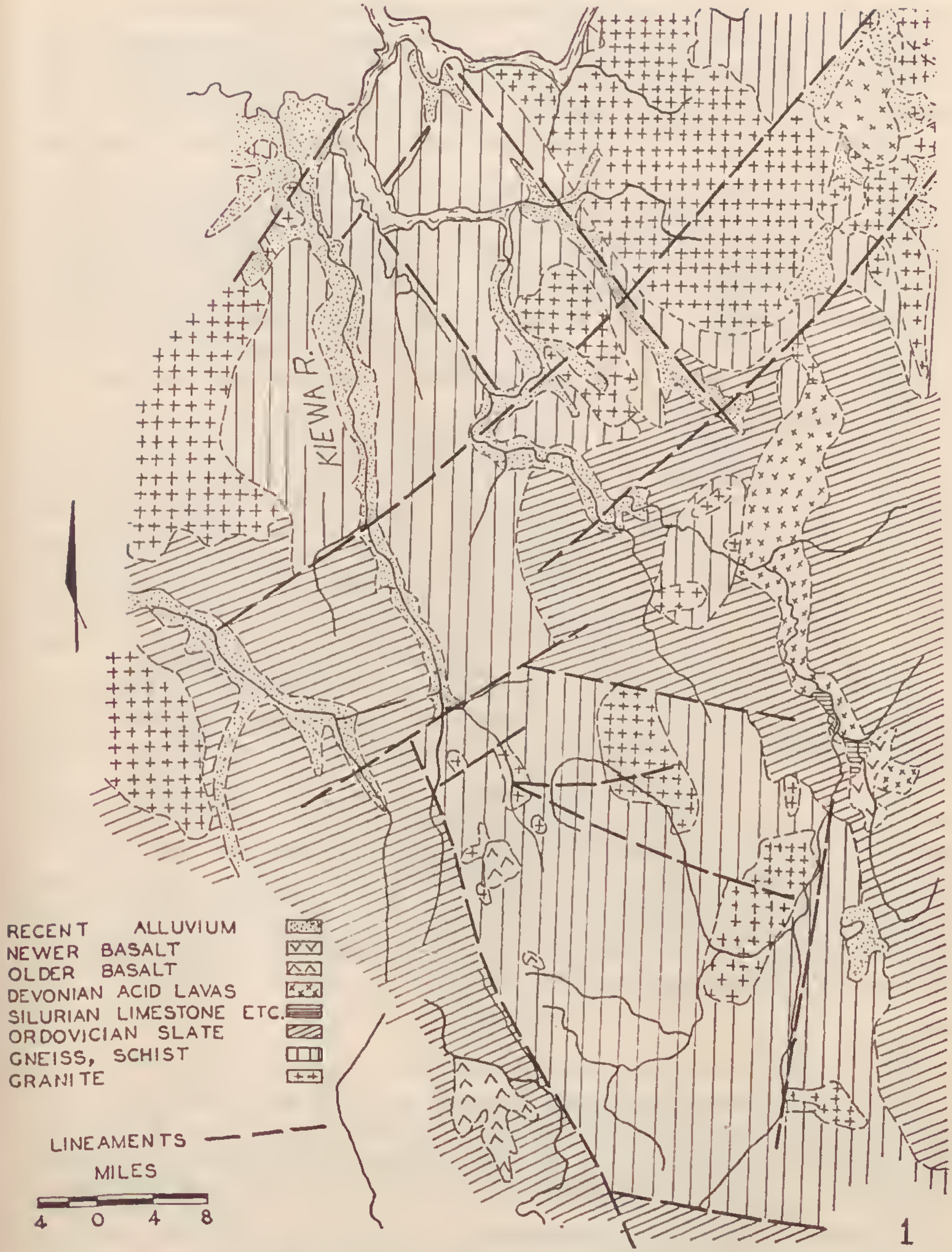
Geology

AGE AND FIELD RELATIONSHIPS

Rocks ranging in age from Upper Ordovician to Recent are exposed in the Kiewa area. The youngest of the Palaeozoic rocks are epi-Middle Devonian in age, while the oldest of the Cainozoic rocks are of Oligocene age. The intervening period apparently was one of non-deposition and erosion. The present distribution of the Cainozoic rocks is very restricted, and it is probable that this was the case even at the time of their deposition and extrusion.

Determination of the age and relationships of the Palaeozoic rocks required examination of sections outside the Kiewa area. Often these factors were determined, of necessity, purely on petrological evidence. Within the area mapped the faulted nature of many of the boundaries necessitated correlation on this basis also. The area is a small sector of the metamorphic complex of NE. Victoria and SE. New South Wales: consideration of local stratigraphic relationships had to be based on the complex as a whole.

Palaeozoic sedimentation occurred in what is known as the Tasman Geosyncline,



1

Fig. 1—Regional Geological Map of part of Metamorphic Complex, NE. Victoria.

and the Palaeozoic stratigraphy of the Kiewa area is to be regarded as part of the sequence of events constituting the history of this geosyncline. It is noteworthy that even the late Tertiary diastrophisms in Victoria were concentrated in this belt, and it is apparent that the mobility of the belt has remained. Moreover, early in the Palaeozoic, parts of the geosyncline ceased to be basins of deposition, and it seems preferable therefore to refer to this belt as the East Australian Mobile Belt (Hills 1956).

A series of orogenies described by David (Browne 1950) have been considered responsible for the folding of the sediments of the East Australian Mobile Belt. These orogenies have been local, e.g. the epi-Ordovician Benambran Orogeny, during which the Upper Ordovician sediments of Kiewa were folded, was restricted to E. Victoria and E. New South Wales. Near Orange, N.S.W., there is no evidence of this orogeny, while in Central Victoria, the passage from the Upper Ordovician to Silurian is conformable. The epi-Silurian Bowning Orogeny was similarly restricted, since in Central Victoria, the Silurian sediments pass conformably up into the Lower Devonian.

The work of Tattam (1929), Edwards and Easton (1937), and Crohn (1949), as well as that of earlier geologists, particularly Howitt, has built up a general picture of the metamorphic complex. The oldest rocks, the Ordovician sediments, range from Darriwilian to Upper Ordovician (Thomas 1949). In some areas, these rocks have been metamorphosed about granites. Apart from this local metamorphism, there is a belt over 100 miles long, and at least 30 miles wide, which has undergone regional metamorphism. There is a marked constriction in this belt near Tawonga, due to faulting, and there is evidence that elsewhere many of the boundaries of the metamorphic belt are faulted (Fig. 1). Much of the E. boundary of the metamorphic belt, however is a normal transition from unaltered Ordovician sediments.

The regional metamorphism is to be dated with the epi-Ordovician Benambran Orogeny. The migmatites ('permeation gneiss') are also this age, and represent the ultimate products of the metamorphism. These migmatites form the core of the complex.

Intrusions of granitic rocks are widespread. These are of two ages: the older are the grey granites and granodiorites, tentatively correlated with the post tectonic phase of the Bowning Orogeny; the younger pink granites and quartz diorites, which at Pine Mountain and Mt Mittimatite intrude the grey granites, are correlated tentatively with the post tectonic phase of the epi-Middle Devonian Tabberabberan Orogeny. Associated with these younger intrusions was a swarm of basic to intermediate lamprophyric dykes. With rare exceptions, the intrusions were post tectonic, only one case of syntectonic intrusion having been recorded.

PALAEOZOIC ROCKS

UPPER ORDOVICIAN SEDIMENTS: THE HOTHAM SLATES

Slates, greywackes, and orthoquartzites occur on the W. flank of the Kiewa area, extending W. from the West Kiewa valley, and typically developed at Mt Hotham. The lithology tends to be monotonous, with slates predominating in the Hotham area, but greywackes become more important further W. Conglomerates and limestones are absent, and the only igneous material is seen in the coarser constituents of the greywacke, which have been derived from granitic rocks. The slates are grey in colour, are sometimes phyllitic, and apparently are unfossiliferous.

T. S. Hall (1908) recorded *Dicellograptus* from Myrtleford, and Harris and Thomas (1941) the following graptolites from Edi:

Climacograptus bicornis
C. bicornis var. *peltifer*
Diplograptus spp.
Dichranograptus nicholsoni var. *parvangulus*
Dicellograptus sp.

From Wombat Cr., Ferguson (1889) recorded:

Dicellograptus elegans
Climacograptus bicornis,

while the present author obtained fragments of *Dicellograptus* and *Diplograptus* from the Rose R. These assemblages are characteristic of an horizon low in the Upper Ordovician. Despite careful search, no fossils were found in the slates at Kiewa, and it has been concluded that the sediments in this area are unfossiliferous.

TABLE 1
Stratigraphic Succession in the Kiewa Area

Age	Formation	Tectonic Episode
Recent	Newer Alluvials	Kosciuskoan Uplift
Pleistocene- Pliocene	Tawonga Gravels Unconformity	
? Miocene- Oligocene (Older Volcanics)	Bogong Volcanics Unconformity	
epi-Middle Devonian	Big Hill Quartz Diorite	Tabberabberan Orogeny
epi-Silurian	Kiewa Granodiorites East Kiewa and Niggerheads Granodiorite Pretty Valley Gneissic Granodiorite	Bowning Orogeny
epi-Ordovician	High Plains Gneiss Mt Nelse Schist	Benambran Orogeny
Upper Ordovician	Hotham Slates	

A detailed traverse along the Kiewa-Eildon power transmission line from the Rose R. to Bright showed no major structural or stratigraphic discontinuity, and this, with the evidence of the typical lithology, is the basis for ascribing an Upper Ordovician age to the slates of the Hotham-West Kiewa belt.

The Benambran Orogeny: High Plains Gneiss and Mt Nelse Schist

Gregory (1902) claimed a pre-Cambrian age for the schists and gneisses, and considered that these were faulted against the Ordovician sediments. Crohn (1949)

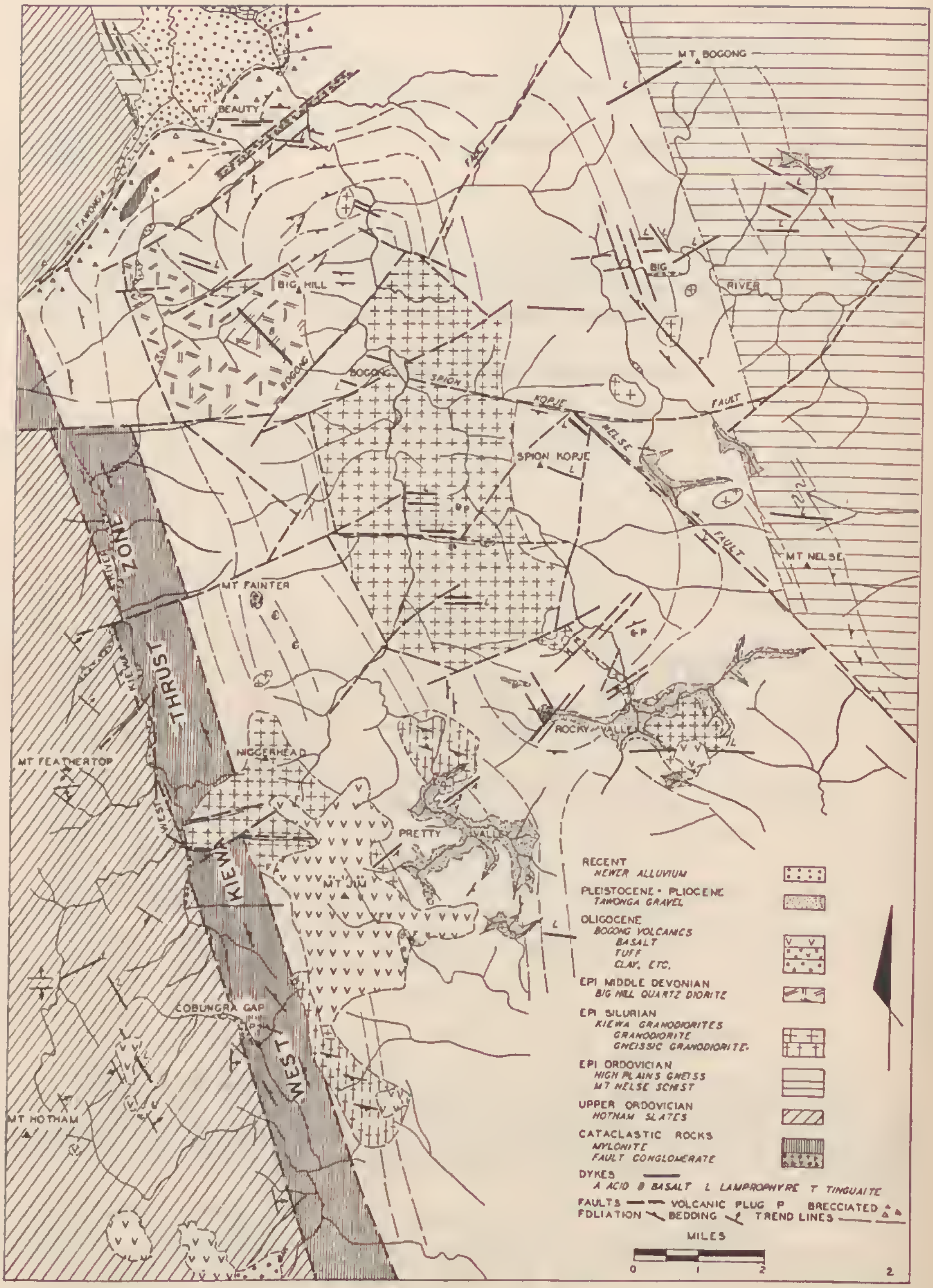


FIG. 2—Geological Map of the Kiewa Area.

considered that two belts of schist occurred: one, a very narrow belt along the W. margin of the area; the other, a wide belt extending easterly from the High Plains to the Mitta Mitta valley. The present author has examined the sediment-schist relationships in both belts, but with particular attention to the W. belt. At Cobungra Gap, one of Gregory's described sections, the chloritic slates are shattered, and pass into low grade schists, having very restricted development. At the Gap, the rocks are brecciated which was doubtless Gregory's evidence for faulting. The low grade schists pass into mylonites which form virtually the whole of the West Kiewa 'schist' belt (Beavis 1961). This mylonite forms the crush zone of the West Kiewa Thrust. Gregory's conclusion that the boundary of the metamorphic rocks at Cobungra Gap is faulted is thus confirmed, although Gregory's picture of the faulting was somewhat different from the present interpretation. Crohn's idea of a normal transition cannot be substantiated in this section.

The Mt Nelse Schists comprise medium to high grade metamorphic rocks which are exposed between Mt Nelse and Mt Bogong. To the W. they are transitional to permeation gneiss, and they are bounded in the N. and in the S. by faults. To the E. there is little doubt of the transition of these schists from the Upper Ordovician sediments; Gregory's dating of the schists as pre-Cambrian was therefore erroneous.

Zones of varying grades of schist were recognized in the field, but actual mapping of the zones was almost impossible. The two main zones in the Mt Nelse area are those of knotted schist, and of biotite sillimanite schist. The zonal boundaries are parallel to the boundary of the gneissic belt. The Mt Nelse Schists are transitional to the W. to the High Plains Gneiss.

In his definition of the High Plains Gneiss, Crohn (op. cit.) included at least the highest grade schists as well as the Pretty Valley Gneissic Granodiorite. These are excluded from the presently defined unit. The High Plains Gneiss is a migmatitic rock, called in this paper 'permeation gneiss', which occupies a belt some 6 miles wide in the N. sector of the area, and up to 14 miles wide in the S. This unit forms the core of the metamorphic complex. The High Plains Gneiss is transitional from the schists, although in part faulted against them. Foliation is continuous through the transition. In the W., the High Plains Gneiss is bounded by the West Kiewa Thrust.

Within the Kiewa area itself, there is no direct evidence of the age of the schists and permeation gneiss. Hills and Thomas (1953) noted that in Eastern Victoria, a tectonic episode occurred at a time that can be dated as post Upper Ordovician and pre Lower Devonian, since the gneiss is overlain with strong angular unconformity by the Lower Devonian Snowy River Porphyries. These authors regard the orogeny—the Benambran—as being of Lower Silurian age, relating it to changes in the conditions of sedimentation in the Central Victorian trough.

Crohn (op. cit.) claimed that the Wombat Cr. Formation succeeded the Upper Ordovician sediments without any break, the boundary between the two being marked by the incoming of conglomerates and limestones. The author has not been able to confirm Crohn's claim. Faulting marks the boundary in part at least, whilst in places there is some evidence of angular unconformity. The age of the Wombat Creek Formation has for some years been in dispute. Ferguson (1889) first described fossils from the formation, and suggested an Upper Silurian age. Chapman (1912, 1917, 1920) referred a number of localities to the Middle Devonian, and the remainder to Yeringian, then regarded as Upper Silurian. J. Talent (1960) considers the age to be pre-Middle to Middle Silurian. The Tambo Formation, of probable Middle Devonian age, rests on the schists with an angular unconformity. This formation has been metamorphosed by the granite porphyry of Mt Sisters.

David (Browne 1950) postulated the formation of a geanticline, consisting of metamorphic rocks, in the East Australian Mobile Belt during the Benambran Orogeny, dated as epi-Ordovician. The evidence presented above tends to confirm this concept, and would date the metamorphism and migmatization as Benambran. The igneous activity (migmatization) is to be regarded as syntectonic.

THE BOWNING OROGENY: THE KIEWA GRANODIORITES

Intrusive into the Ordovician sediments, the schists, and the permeation gneiss are two suites of granitic rocks. The older of these are the grey granodiorites and gneissic granodiorite. David (Browne op. cit.) dated the granites and diorites of the Yackandandah district, as well as some of the Kiewa intrusives, with the Bowning Orogeny of epi Silurian age. Crohn (op. cit.) recognized two suites of intrusives in the Omeo-Kiewa area, and whilst he was not specific, it would appear that he referred the grey granodiorites of Kiewa to the older suite.

There is no direct evidence at Kiewa which would justify certain correlation of the granodiorites with the Bowning Orogeny: they are certainly younger than the Benambran permeation gneiss, and older than the ? Tabberabberan quartz diorite. Talent (1960) has found definite evidence of Bowning intrusion in NE. Victoria in the Berridale Granite, but has found no evidence of Benambran intrusion.

At Kiewa, two phases of Bowning intrusion are recognized. The first was the syntectonic intrusion of the Pretty Valley gneissic granodiorite, the second, the normal post-tectonic intrusion of normal granodiorites. The Pretty Valley Gneissic Granodiorite is exposed in two adjoining areas on the Bogong High Plains between Pretty Valley and the Bundarrah R.; it is possible that continuity may exist at shallow depth. The gneissic granodiorite has the composition of a normal granodiorite, but it is strongly foliated, and has a discontinuous banding. The gneissic granodiorite is intrusive into the permeation gneiss on which a thermal metamorphism has been imposed. The margins of the gneissic granodiorite transgress the foliation of the permeation gneiss, but the long axes of the somewhat elliptical shaped masses of the gneissic granodiorite are parallel to the structural trend of the country rock. This is of interest since the foliation of the gneissic granodiorite is almost normal to this trend.

Included in the gneissic granodiorite are xenoliths and roof pendants of biotite sillimanite schist and metaquartzite. These are frequently elliptical in plan, with the long axes parallel to the foliation of the host rock. Some are banded with pegmatic material. The rocks constituting the xenoliths are typical of the highest grades of schist, the nearest present exposures of which are at Mt Nelse, some miles to the N. None the less, some lenses of these rocks are to be found in the mylonite belt of the West Kiewa Thrust, and it is apparent that the schists may have been present at Pretty Valley at the time of intrusion of the gneissic granodiorite.

The contact between the gneissic granodiorite and the permeation gneiss was observed both at the surface and in the No. 1 Head Race Tunnel. The tunnel section showed reaction between the two rocks, as well as the localized metamorphism and the concentration of acid dykes at the contact. The more southerly mass intrudes not only the permeation gneiss but also the West Kiewa mylonite, in which a very narrow contact aureole has been developed. This mass is elongated along the margin of the Thrust, and some control of the intrusion by the Thrust zone may have been exerted.

Two main masses of normal granodiorite occur: the Niggerheads and the East Kiewa. The former, with normal intrusive contacts against the permeation gneiss and the West Kiewa mylonite, is faulted against the Upper Ordovician sediments in the West Kiewa Valley. The Niggerheads mass has a crudely rectangular form, with the long axis parallel to the regional trend of the country rock. This is also true of the East Kiewa Granodiorite, exposed in the East Kiewa Valley; most of the contact of this mass, however, is faulted. Where the contacts are normal, as on the flanks of Spion Kopje, and at Langford's Gap, a contact aureole some 500 ft wide has been developed in the permeation gneiss.

Numerous small masses of granodiorite and granodiorite aplite occur throughout the area. One of these, a richly garnetiferous granodiorite, is intrusive into the Pretty Valley Gneissic Granodiorite. Recrystallized granodiorite aplites outcrop on Timm's Lookout, on the spur running down from the Lookout to Big R.-Cairne Cr., and as an inlier in the Newer Alluvials at Tawonga South. Localized recrystallization has been observed in the East Kiewa Granodiorite. The most extensive area is at Bogong township, where the recrystallized rock forms bold, fresh, outcrops in contrast to the deeply weathered normal granodiorite.

All of the granodiorites show strong petrographic similarities with those of Yackandandah and elsewhere in the region which David (1950) dates with the Bowning Orogeny. The close of this orogeny at Kiewa was marked by intense faulting, the first movement on the Tawonga Fault probably being of this age.

THE TABBERABBERAN OROGENY: THE BIG HILL QUARTZ DIORITE

The Big Hill Quartz Diorite is intrusive into permeation gneiss and granodiorite. At the contact with the latter, a complex of alkaline syenitic rocks occurs. All of these are deeply weathered, and exposures were too restricted for detailed study. Where the quartz diorite is exposed at higher altitudes, melanocratic schlieren are abundant. These are absent at lower altitudes, suggesting that the higher exposures are close to the original roof of the pluton.

The S., W., SE., and part of the N. boundaries are faulted. There is some evidence, discussed in a later section, that the quartz diorite was originally in direct contact with the East Kiewa Granodiorite, with displacement occurring along the Bogong Fault. In the Lower West Kiewa Tunnel the contact of the quartz diorite with permeation gneiss was exposed. This contact is very sharp, with only a 10 ft zone of thermal metamorphism recognizable in the gneiss.

Lamprophyre dykes have intruded all of the Palaeozoic rocks in the Kiewa area, including the quartz diorite. These dykes are much younger than the pegmatite dykes, many of which are cut by lamprophyres. The relationship between the lamprophyres and the Tertiary rocks is seen in Rocky Valley where a hornblende lamprophyre intrudes the granodiorite, and is overlain by the basal flow of limburgite at Basalt Hill. Although the survey of Crohn covered a wider area than that of the writer, no evidence was found to substantiate the former's claim that the lamprophyres are restricted to the margins of the main gneissic belts. Several thousands of these dykes have been mapped, and their distribution appears to be uniform. There is a close relationship between the crush zones of faults and the dykes, which frequently occur on the walls of the crush zones. The pattern of distribution is consistent in the tendency for the dykes to occur in groups of 3 to 5, closely spaced, but with some hundreds of feet between groups.

CAINOZOIC ROCKS

THE BOGONG VOLCANICS

The Bogong Volcanics are defined as a formation comprising basalts, with lesser phonolites, and doleritic and alkaline dykes; associated with the lavas are gravels, sands, clays, tuffs, and brown coals, the sediments often fossiliferous. The Formation is restricted to the Bogong High Plains and the higher parts of the adjacent mountain areas. Excluding the pyroclastics, two main types of sediment have been recognized. Lacustrine sediments occur below and intercalated with the basalts of the High Plains: fluviatile sediments are exclusively sub-basaltic and are restricted to Mt Fainter and the Hotham area.

Beneath the basalt of Mt Fainter, some 30 ft of river gravels are exposed. At Hotham Heights, excavations at White's Mine have exposed a considerable thickness of these gravels together with associated fluvio-lacustrine sediments, some of which contain poorly preserved plant remains. A typical section, now largely obscured, has been described by Kenny (1937):

	Ft
Surface soil	3
Sands	10
Ligneous clays	15
Gravel	30
Ligneous clay and sand	20
Gravels	20–30
Hotham Slates	

By contrast, the sub-basaltic sediments of the High Plains are purely lacustrine, and are richly fossiliferous. The section on the Bundarrah R., first described by Murray (1878), and later by Crohn (1949) is now known in more detail:

	Ft
Basalt	
Sandy clays and sand	4
Brown coal	1
Red and grey fossiliferous shale	1
Grey, poorly fossiliferous shale	2
Micaceous sandy clays, in part tuffaceous, with stumps	14
Mottled grey and brown clays	14
Gneiss	

The best known sequence of inter-basaltic sediments is at West Dyke, where close drilling was carried out:

	Ft
Basalt	
Tuffaceous clays (? soil)	4
Yellow silty clay	5
Grey fossiliferous shale	1
Brown Coal	1
Grey fossiliferous silty clay ..	19
Basalt	

At 'The Lake', landslides have exposed thick, massive sandstones, with leaf impressions, and thin, richly fossiliferous shales. Elsewhere about the basalts of Mt Jim, outcrops of fossiliferous clays have been observed. Fossils recorded from these sediments include:

Drypteris dargoensis
Taeniopteris tennuissime striata
Phyllocladus sp.
Agathis sp.
Araucarias sp.
Insectae indet.

The brown coal is comparable in composition and moisture content to the oldest of the Latrobe Valley coals, which may be as old as Eocene. The Kiewa flora suggests an Oligocene to Miocene age (O. Selling, personal communication), but precise age determination is not possible.

Basalts, limburgites, and alkaline differentiates occur in two relatively restricted areas: on the Bogong High Plains, between Rocky Valley and the West Kiewa R., and in the Mt Hotham-Upper Ovens area. The most important occurrences on the High Plains are Basalt Hill, Ruined Castle, and Mt Jim, with a small outlier on Mt Fainter, and plugs on Junction Spur, Roper's Lookout, Rocky Cr., and Cobungra

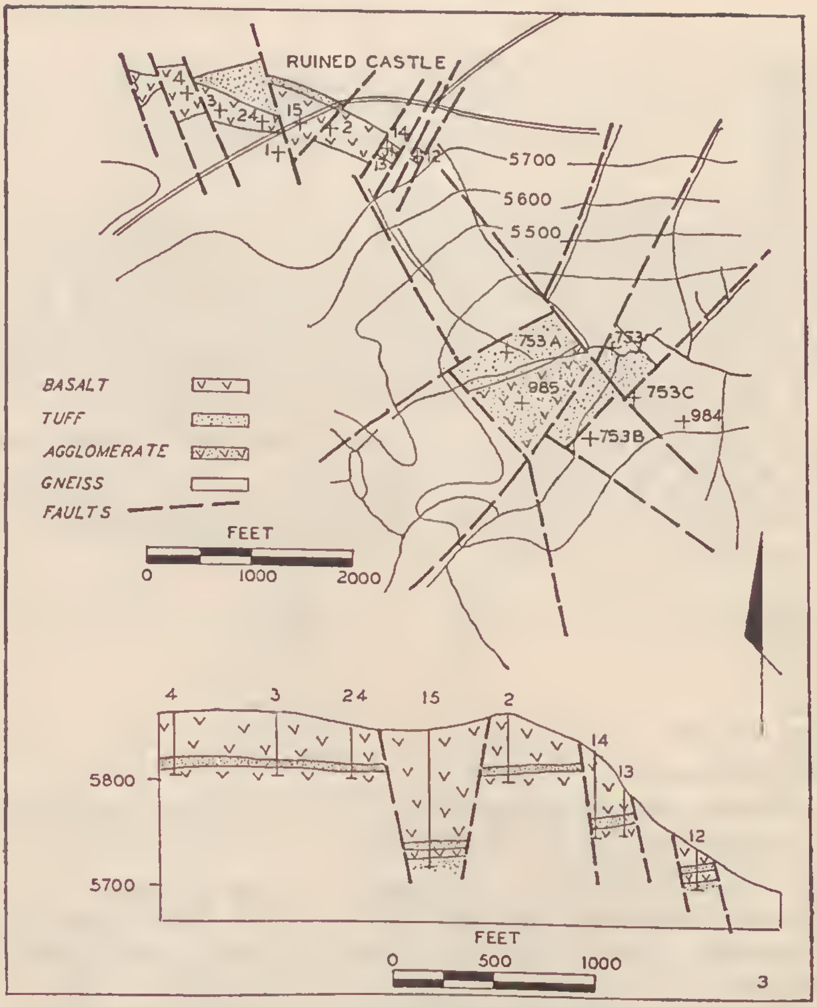


Fig. 3—Basalts at Ruined Castle and Rocky Cr.

Gap. The occurrences at Hotham include Mt Hotham, Mt Loch, Mt Higginbottom, and the phonolite of Mt Smythe. The lavas form some of the higher, but not the highest, parts of the terrain.

Three flows may be recognized at Basalt Hill. The basal flow is a limburgite, with thickness ranging between 30 and 180 ft. The middle flow, olivine basalt, is 30 to 90 ft thick, while the upper flow, also olivine basalt, forms a veneer only 15 ft in thickness. No sub- or inter-basaltic sediments occur, but scoriaceous material was observed at the base of the lower flow.

At Ruined Castle, the extent of the basalts and tuffs is greater than that indicated by Cottle (1947), and moreover, the relationships are considerably more complex. Faulting has been extensive, and it is due to this deformation that the columns show gross irregularities of plunge. Tuff, at least 50 ft thick, is faulted against the N. edge of the basalt (Fig. 3). Basalts and tuffs alternate:

	Ft
Basalt	51–110
Tuff	12
Basalt	9
Tuff	5
Basalt	6
Tuff	7
Basalt	6
Tuff	10
Basalt	1
Tuff	8
Basalt	2
Tuff	50
Basalt	5

Cottle's suggestion that the basalts and tuffs occupy an old river valley cannot be confirmed with the evidence available. Nowhere has a bore penetrated to bedrock. Variations in the level of the base of the uppermost flow, as well as the rectilinear boundaries are due to faulting. The adjacent Rocky Cr. basalt-tuff-agglomerate association is also faulted. The bore evidence alone suggests that this association marks a point of eruption, but the more than 300 ft thickness of pyroclastics in bore 753A can also be explained in part by downthrow along mapped faults. In view of the nature of the materials, there seems little doubt that this is a locus of eruption, modified by faulting.

The 7 flows of olivine basalt and limburgite at Mt Jim constitute the largest outlier of volcanic rocks in the Kiewa area. Together with intercalated sediments, the total thickness is over 500 ft:

	Ft
Basalt	70
Sands, coal, etc.	30
Basalt	52
Tuffs	2
Basalt	35
Clay, coal, tuff	94
Basalt	49
Clay and coal	5
Basalt	30
Sandstone	6
Basalt	33
Clay, coal, tuff	36
Limburgite	30
Clay, sand, coal	80
Gneiss	

Both Dibbin's Lookout (limburgite) and Young's Lookout (olivine basalt) are outliers from the main Mt Jim series. There is no evidence that Dibbin's Lookout is a plug (cf. Edwards 1938).

Hills (1939) citing Condon's description of Roper's Lookout as a denuded cone, considered a possibly young age for some at least of the basalts. Very close field examination of this feature, with Condon's field notes available, failed to verify this interpretation. Roper's Lookout is rather to be regarded as a plug.

Although olivine basalts predominate in the Hotham area, this area differs from the High Plains in the occurrence of phonolites, the most important of which is Mt Smythe. Nowhere in the area has a direct field relationship between the basalts and the phonolites been observed.

Dykes of dolerite, olivine basalt, and tinguaite occur sporadically. These are tentatively correlated with the Bogong Volcanics on petrological grounds, although the dolerites show some affinities to the lamprophyres, as do some of the basalt dykes. The petrological evidence alone is frequently inconclusive.

The age of the olivine basalts and associated lavas is almost certainly Lower Cainozoic, because of their intimate association with plant beds of this age. The basalts are therefore to be correlated with the Older Volcanic rocks of Victoria. As stated above, Hills tentatively suggested a possibly younger age for part at least of the Bogong Volcanics, while Thomas (1949) referred to Mt Jim as a possible locus of eruption of late Cainozoic age. In fact, Mt Jim is a remnant of the formerly more extensive uppermost flow of the outlier. The columnar jointing is regular, and this, together with the complete absence of pyroclastics suggests that Thomas's idea was not valid.

THE KOSCIUSCO UPLIFT: LATE CAINOZOIC ALLUVIALS

Uplift of the Kiewa area during movement on the Tawonga Fault is regarded as a phase of the more general Kosciusco Uplift, dated by David as late Pliocene, but as even younger by Jaeger and Browne (1958). Later discussion in this paper will develop the writer's idea that movement began in the early Cainozoic, and persisted to the Pleistocene.

Two formations of late Cainozoic alluvium have been recognized in the area: the Older Alluvials (Tawonga Gravel) and the Newer Alluvials. The Tawonga Gravel comprises medium to coarse gravels, typically developed near Tawonga, where the thickness may exceed 200 ft, and where they are conformably overlain by the Newer Alluvials. They occur in the mature valleys of the High Plains, also, where thickness is rarely greater than 10 ft. These sediments are typically fluviatile, and show no evidence of a lacustrine origin (cf. Carr and Costin 1955). The Tawonga Gravel was involved in movement on the Tawonga and Sassafras Creek Faults.

The Newer Alluvials are of two types: peat, up to 5 ft thick, in the sphagnum bogs of the High Plains, and sands and gravels, currently being deposited on the valley floors. These sediments do not appear to have been involved in fault movements, which apparently ceased in the Pleistocene.

Pleistocene glaciation in the area was first discussed by Stirling (1886), and later by Crohn (1949) and by Carr and Costin (1955). It is clear (Beavis 1959) that no evidence of such glaciation is to be found in either the late Cainozoic sediments or in the physiographic features.

Petrology

Petrological studies by Tattam (1929) in Victoria, and in New South Wales by Joplin (1942, 1944, 1947) showed the essentially thermal nature of the metamorphism in the metamorphic complex. The petrological work described in this paper adds little that is new to our knowledge of the metamorphic rocks, with the exception of the recognition of the importance of shearing stress on a local scale in the late and post metamorphic periods. The study of the igneous rocks is more important since these have not been described previously; moreover, the petrology was frequently the sole basis for the correlation of these rocks with others outside the area, the age of which is known.

UPPER ORDOVICIAN SEDIMENTS: THE HOTHAM SLATES

On the immediate W. flank of the Kiewa area the sediments of this age are dominantly pelitic, but further W., near Bright, subgreywackes, greywackes, and quartzites become more important. The chemical analyses of these rocks (Table 2) demonstrate that the sediments are rich in alumina and potash, and in fact, that the alumina content of the slate is abnormally high. Tattam (op. cit.) recorded a slate from Mt Wagra with 24% alumina, so that excessively aluminous slates may not be uncommon in this area. The sedimentary assemblage is characteristic of the late stages of geosynclinal deposition: particularly important in this regard is the pronounced development of greywackes (Pettijohn 1957).

In the hand specimen, the slates appear to be uniform, but in thin section fine internal stratification is well marked. The main constituents are fine quartz, rare felspar, sericite and chlorite. Recrystallization of sericite to muscovite and of chlorite to biotite was observed. The greywackes occur in thin beds and, unlike the slates, lack any internal stratification; graded bedding is characteristic. These sediments are composed of angular to subangular grains of quartz, oligoclase, rare orthoclase and microcline, all of which show authigenic sericite on the grain boundaries. The coarse constituents are set in a matrix of finer quartz, and sericite and chlorite, with occasionally some secondary calcite. Detrital almandine, tourmaline, magnetite, and more rarely zircon and andalusite occur as heavy accessories. More arenaceous types, transitional to quartzites, are composed of subangular grains of quartz, with felspar very rare, in a quartzose matrix, which contains a little sericite and chlorite. The quartzites are composed almost exclusively of subangular grains of quartz, on which are secondary outgrowths of quartz. Felspar is very rare, and only occasionally was sericite observed.

TABLE 2

Analyses of Upper Ordovician Sediments

	1	2	3
SiO_2	50·64	62·95	77·68
Al_2O_3	24·55	18·35	11·69
Fe_2O_3	2·32	4·28	1·68
FeO	4·44	0·56	1·91
TiO_2	0·83	0·65	0·10
CaO	0·25	0·98	0·43
MgO	2·61	1·65	1·52
Na_2O	0·30	0·42	0·90
K_2O	5·95	3·85	2·59
MnO	0·03	—	0·02
P_2O_5	0·05	0·15	—
H_2O-	0·32	0·50	0·26
H_2O+	6·65	6·34	2·29
	98·94	100·68	101·07

Analyses: V. Biskupsky

	4	5
Quartz	32·3	63·1
Oligoclase	15·9	10·7
Orthoclase	3·5	tr.
Mica	0·9	2·1
Matrix	46·0	22·5
Accessories	1·4	1·6
	100·0	100·0

1. Slate, Mt Hotham; 2. Greywacke, Bright; 3. Quartz sandstone, Mt Feathertop; 4. Same specimen as 2; 5. Same specimen as 3.

MT NELSE SCHISTS

Within the area studied low grade schists were observed only as thin lenses in the mylonites of the West Kiewa Thrust Zone. The schists of the Mt Nelse-Mt Bogong belt are high grade types, in which a distinct zoning may be recognized. The low grade schists of West Kiewa are strongly foliated, and are composed of quartz and very fine flakes of light brown mica. A little calcic felspar and epidote may also be present. The lowest grade schists of the main belt are those exposed on T Spur, Mt Bogong. These are fine textured, strongly foliated rocks, with locally, a tendency to banding. Porphyroblasts up to 5 mm in diameter stand out as ellipsoidal knots on the weather surface, and develop a strong lineation. In thin section the knots are seen to be zoned, with an outer zone of fine pinite, and a core of coarser pinite, muscovite, anhedral to subhedral biotite, and minute crystals of cordierite and quartz. The matrix of the rock is composed of fine flakes of biotite and needles of quartz. Associated with each knot is a 'tail' of quartz which imparts the apparent banding to the schist. The 'tails' may contain some felspar and cordierite. The foliation of the matrix curves around the knots, while quartz rich 'tails' terminate abruptly against them. This schist has the mineral assemblage of the hornblende hornfels facies of Fyfe, Turner and Verhoogen (1958).

The fine pinitic material was examined by X-ray diffraction (Table 3). The data obtained, and particularly the fineness of the 10A line, suggest that shearing stress was not responsible for the retrograde development of pinite from cordierite, confirming Tattam's conclusion that the pinitization was a retrograde thermal feature. No doubt exists that the pinite was derived from cordierite, both from the evidence in thin section, and that of the X-ray study. Walker (1950) showed that the position of the (060) reflection can be used to determine whether the mica is dioctohedral or trioctohedral. In this pinite the (060) reflection occurs at 1·56 kx indicating a trioctohedral type, derived from cordierite.

TABLE 3

X-ray Powder Pattern: Pinite

I (est.)	8	3	5	1	10	6	4	2	3	1	2	½
d (kx)	10·02	5·04	4·52	3·73	3·52	3·27	2·51	2·49	1·78	1·67	1·56	1·48

The knotted schist from Mt Nelse-Timm's Lookout is a higher grade type than that of Mt Bogong. The knots are composed of poikiloblastic aggregates of pinite; the inclusions are cordierite, flakes of muscovite, strained quartz, and strongly pleochroic green brown biotite. Surrounding the knots is a rim of dark brown biotite, sometimes partly replaced by sillimanite and sometimes bleached, the transition from brown to colourless biotite sometimes occurring within the length of a single crystal. Almandine is frequently intimately associated with the biotite, and tourmaline is relatively common. The matrix of this schist is composed of quartz, frequently strained, and enclosing needles of sillimanite. Biotite and deformed muscovite also occur in the matrix, together with andesine and partly pinitized cordierite. There is some evidence in the strained quartz that this rock has been subjected to post recrystallization shear, probably associated with movements on the nearby Nelse and Spion Kopje Faults.

Interbedded with the knotted schists at Mt Nelse are strongly foliated, fine to medium textured quartz hornblende almandine schists. These are composed of quartz, strongly poikiloblastic cordierite, almandine, oligoclase, and abundant green, lime rich amphibole. Magnetite and tourmaline are secondary accessories.

Both on Mt Bogong and Mt Nelse the knotted schists pass up into higher grade quartz felspar sillimanite cordierite almandine biotite schist. In one specimen from T Spur, traces of the knots may be seen, but the pinite largely appears to have been recrystallized to muscovite. Quartz enclosing sillimanite shows strain. The cordierite is strongly poikiloblastic. The biotite is green brown, strongly pleochroic, and contains numerous minute inclusions of black iron ore. Andesine and almandine occur in accessory proportions only. Some secondary tourmaline is always present. At Aertex Hut on the same spur, sillimanite increases in importance.

In Big R., the schist is very coarse textured (crystals up to 3·5 mm) and strongly foliated. Quartz, oligoclase-andesine, dark brown, almost opaque, biotite, sillimanite and muscovite are the essential constituents, with almandine occurring sporadically.

These schists have mineral assemblages of the hornblende hornfels facies, with features suggesting transition to the almandine amphibolite facies. The quartzo-felspathic assemblage seen in the quartz amphibole almandine schist does not appear to have been described previously, but the intimate field association with the knotted schists indicates that it is an assemblage of the same facies. It is to be noted that the knotted schists of Mt Bogong do not show the transitional aspects of those of Mt Nelse.

TABLE 4

Chemical Analyses of Schists

	1	2	3	4	5	6
SiO_2	75·45	66·71	56·90	99·35	72·49	52·70
Al_2O_3	13·76	16·48	21·85	0·65	14·78	24·10
Fe_2O_3	1·21	0·45	0·65	0·05	0·88	1·68
FeO	2·09	4·10	3·98	—	2·20	4·63
TiO_2	0·51	0·70	0·71	0·01	0·51	0·52
CaO	0·24	0·54	0·78	—	6·82	0·27
MgO	1·40	2·41	2·09	—	1·11	3·46
Na_2O	0·45	0·58	0·64	—	0·45	0·51
K_2O	3·47	4·22	5·93	—	tr.	6·84
MnO	0·03	0·07	0·04	—	0·05	0·04
P_2O_5	0·08	0·10	0·09	—	0·15	nd
H_2O-	0·12	0·35	0·67	0·03	0·21	0·26
H_2O+	2·01	3·05	5·15	0·02	0·69	4·85
	100·82	99·76	99·48	100·11	100·34	99·86

1. Low-grade quartz biotite schist, Cobungra Gap; 2. Quartz biotite almandine schist, West Kiewa; 3. Knotted schist, T Spur, Mt Bogong; 4. Quartz schist, Mt Nelse North; 5. Quartz amphibole almandine schist, Mt Nelse; 6. Pinite from knotted schist (Tattam 1929).

Analyses: V. Biskupsky

The analyses illustrate the wide variations in the schists. The nature of the amphibole in the quartz amphibole almandine schist is seen in the high lime content of this rock. This rock, and a xenolith from the permeation gneiss are the only two examples of lime rich sediments in the area. The importance of additions of potash during the pinitization of the cordierite of the knotted schist is to be noted in analysis 3. The alumina content of analysis 3 also suggests derivation from pelitic sediments, while the rocks of analyses 1, 2, and 5 appear to have been derived from greywackes.

Where the schists have been intruded by later granodiorites, the most important feature of the resulting contact metamorphism has been the development of sillimanite at the expense of biotite. Near Mt Nelse, the knotted schists, where they are in contect with granodiorite have been completely recrystallized, with the development of crystals of pink, strongly pleochroic andalusite, up to 5 in. long.

PERMEATION GNEISS: HIGH PLAINS GNEISS

The permeation gneiss is markedly heterogeneous both in composition and texture. Foliation and banding, with some notable exceptions, are well developed, and almost certainly have been inherited from the original sediments. In the field the permeation gneiss is characterized by both banding, and the frequent occurrence of biotite rich lenses and pegmatitic quartz-potash felspar nodules, up to 2 ft long. Macrobands of nonfoliated gneiss occur. These are probably representatives of Tattam's granulite, and may represent the quartzitic beds of the original sediments. Xenoliths occur in the permeation gneiss. These are of two types, one gneissic, and transitional in composition between high grade schists and the gneiss itself, the other type is hornfelsic, and includes a wide range of petrographic types.

Sillimanite and cordierite are typical constituents of the permeation gneiss, although the latter is frequently pinitized. Quartz, biotite, and felspar are the other essential constituents. Almandine occurs commonly, but always in accessory proportions. The quartz usually encloses needles of sillimanite, and may show myrmekitic intergrowth with alkali felspar near the crystal boundaries. Orthoclase, orthoclase perthite, and more rarely microcline are usually in excess of andesine, although in some cases the andesine predominates. Biotite is of two types: one dark brown, almost opaque, with inclusions of zircon around which pleochroic haloes have been formed; the other is a light brown variety, lacking inclusions, and strongly pleochroic. This clearly indicates two generations of biotite. Another important distinction is that while the dark biotite is replaced to some degree by sillimanite, this replacement is lacking from the lighter variety. The sillimanite occurs as rods in the quartz, and as felted masses after biotite. Although cordierite is invariably present, pinitization has occurred, with subsequent recrystallization of the pinite to muscovite. Some of the white mica observed in the gneiss is bleached biotite. Apatite, zircon, sphene and rutile are common accessories.

The nonfoliated gneiss has a greatly reduced content of biotite, sillimanite, and cordierite. The texture is coarse, granoblastic, and the essential constituents are quartz, orthoclase, orthoclase microperthite, andesine, and sometimes white mica. Biotite and sillimanite are to be regarded as accessories only. Almandine also occurs as an accessory.

The leucocratic lenses in the gneiss have a pegmatitic texture and may represent segregations, or later additions, of granitic magma. Crystals of quartz, and felspar, showing pegmatitic intergrowth are up to 5 mm in diameter. The felspar is orthoclase, orthoclase microperthite, or commonly, microcline. Andesine is rare, and muscovite is sporadic. Almost invariably these nodules are surrounded by a zone of biotite rich material. The biotite flakes have a preferred orientation parallel to the margins of the nodules, and may indicate reprecipitation after reconstitution of the original rock. The biotite rich melanocratic lenses are composed essentially of biotite, sillimanite, and rare quartz and muscovite. Sillimanite has almost completely replaced the biotite.

Xenoliths in the permeation gneiss are most common near Mt Cope. The commonest type shows a moderately strong foliation due to parallelism of biotite flakes. The biotite is light brown in colour, and pleochroic. Quartz, orthoclase, and andesine are abundant, while almandine may be abundant or present only in minor amounts. Another type, with granoblastic texture, is composed of quartz, almandine, and biotite. One group, which is fairly common, has only a weak foliation, but with blastoporphyritic texture well developed. Green, strongly pleochroic amphibole occurs in a fine matrix of quartz, andesine, orthoclase, and almandine. A similar textural type has large porphyroblasts of diopside in a quartz-felspar matrix. This assemblage is of considerable interest, since it is a typical calcareous assemblage of the pyroxene hornfels facies, and is the other of the two indications of lime rich sediments previously noted.

The permeation gneiss has been thermally metamorphosed where it has been intruded by later granodiorites. Typical of the metamorphism is the development of porphyroblasts of mauve cordierite. This is clearly seen at Langford's Gap in Rocky Valley. In some cases, as on Spion Kopje, the calcic cores of the plagioclase have been replaced by clinozoisite. Almandine is also characteristic of the contact zones, while the quartz is spongy with inclusions.

TABLE 5

Analyses of Permeation Gneiss

	1	2
SiO_2	70·49	72·65
Al_2O_3	17·13	16·81
Fe_2O_3	1·04	1·07
FeO	1·56	2·08
TiO_2	0·36	0·40
CaO	1·40	0·80
MgO	1·31	1·29
Na_2O	1·60	1·50
K_2O	2·80	2·50
MnO	0·04	0·05
P_2O_5	0·03	0·04
H_2O-	0·13	0·13
H_2O+	1·30	1·35
	99·79	100·67

Analyses: V. Biskupsky

	3	4	5	6	7	8	9	10	11	12
Quartz	69·3	13·4	31·6	59·0	62·0	53·1	0·7	80·9	83·1	78·8
Orthoclase	tr.	—	—	1·6	1·3	6·3	—	2·7	1·3	3·2
Microperthite	4·3	40·0	1·0	—	—	—	—	—	—	—
Microcline	—	41·5	—	—	—	—	—	—	—	—
Plagioclase	6.2	—	61·5	18·8	4·0	3·9	—	1·0	1·6	1·0
Biotite	13·5	—	3·2	16·0	13·3	28·2	86·7	7·6	13·5	13·1
Muscovite	—	5·1	2·4	1·0	4·5	5·7	10·2	—	—	—
Cordierite	1·7	—	tr.	0·3	1·1	tr.	—	0·1	—	—
Almandine	tr.	—	—	—	tr.	—	—	7·1	—	—
Sillimanite	4·5	—	tr.	1·7	11·3	1·9	2·1	—	—	0·4
Accessories	0·5	tr.	0·3	1·6	2·5	0·9	0·3	0·6	0·5	3·5

1. Permeation gneiss, Rocky Valley; 2. Leucocratic lens, Rocky Valley; 3. Permeation gneiss, Rocky Valley; 4. Leucocratic lens, Rocky Valley; 5. Permeation gneiss, No. 4 Power Station; 6. Permeation gneiss, No. 4 Head Race Tunnel; 7. Permeation gneiss, Clover Dam; 8. Permeation gneiss, Clover Dam; 9. Biotite rich lens, Fall's Cr.; 10-12. Xenoliths in gneiss, Mt Cope.

INTRUSIVES: PRETTY VALLEY GNEISSIC GRANODIORITE

With the essential composition of a granodiorite, the Pretty Valley gneissic granodiorite has a well developed foliation, and discontinuous, somewhat lenticular banding. The rock mass is relatively homogeneous, with very little variation in composition or texture. Quartz occurs as anhedral pools up to 2 mm in diameter, sometimes with corroded margins. In a few specimens, orthoclase was in excess of oligoclase-andesine, but overall, the ratio of orthoclase to plagioclase is 1 : 3, with the rock of the more southerly mass particularly showing a much reduced orthoclase content. The plagioclase is frequently idiomorphic, and may be enclosed in quartz; sometimes the felspar occurs as groups of crystals crowded between large pools of quartz. In one specimen from Pretty Valley dam site, the plagioclase occurs as anhedral crystals 4 mm in diameter, the cores are sericitized, and are surrounded by oligloclase, with shadow zoning and twinning. Micrographic intergrowths of quartz and felspar were noted occasionally. The biotite is light brown in colour, and has been locally chloritized. Replacement of biotite by sillimanite was noted, but this is rare. Almandine is sometimes associated with the biotite. Cordierite, zircon, apatite, and sphene are accessories. Secondary chalcopyrite and clinozoisite are present along joints.

The large rafts of schist which occur at Pretty Valley have been partially granitized. Myrmekitic and micrographic intergrowths of quartz and felspar are common. Orthoclase and plagioclase are present in equal proportions; the felspars are frequently poikilitic enclosing minute crystals of biotite and quartz. The biotite is generally bleached, and is partly replaced by sillimanite. Fine needles of sillimanite also occur in the quartz. Almandine and cordierite are essential constituents, the latter often pinitized.

A series of acid dykes is intimately associated with the gneissic granodiorite. Many of these are quartz-potash felspar pegmatites; a few are aplites. The aplites have a sugary texture, with relatively large (0·8 mm) crystals of quartz and orthoclase common, and andesine, less common. There is a tendency for the biotite to be segregated about the grain boundaries of the plagioclase. At Pretty Valley North, almandine is an essential constituent.

Granite dykes are also relatively common. These have a medium (2 mm) hypidiomorphic texture. Orthoclase and microcline are in excess of sodic oligoclase. Quartz is abundant, and is euhedral. Muscovite, poikilitic, and partly resorbed, is in excess of biotite. Cordierite, apatite and zircon are accessory.

INTRUSIVES: NIGGERHEADS AND EAST KIEWA GRANODIORITES

The Niggerheads granodiorite is a medium textured rock, composed of anhedral crystals of quartz, andesine and orthoclase, with the former dominant, and green brown biotite. The biotite is commonly replaced by clinozoisite and magnetite, while plagioclase, with sericitized cores, is often enclosed in the biotite. Apatite and zircon are accessory. A fine grained phase is present on the E. margin of the mass. Crystal size is rarely greater than 0·7 mm. The composition is the same as that of the coarser rock, but the andesine is poikilitic, and cordierite is an important accessory.

While the Niggerheads granodiorite is reasonably uniform, wide variations in both texture and composition occur in the East Kiewa granodiorite. Most of the variations appear to be the result of shear and metasomatism (Baker 1950). At Bogong Village the granodiorite has a medium (1·0-1·3 mm) even texture, with quartz, orthoclase, microcline, andesine and biotite the main constituents. Further N., green-brown, strongly pleochroic hornblende becomes important, and at the N. margin, is in excess of biotite. It is not unusual for the hornblende to have a core of light brown biotite. In the N. the biotite is replaced by magnetite in a number of localities.

At Windy Gap near Rocky Valley, the quartz is subhedral to euhedral, in contrast to the generally anhedral form elsewhere. Here also, muscovite is an essential constituent. At No. 1 Power Station a fine, very dark variety occurs, with biotite the main constituent. In Rocky Valley, between Howman's Gap and Bogong

TABLE 6

Analyses of Gneissic Granodiorite

	1
SiO_2	64·36
Al_2O_3	20·41
Fe_2O_3	1·65
FeO	2·96
TiO_2	0·41
CaO	4·63
MgO	1·48
Na_2O	1·55
K_2O	2·11
MnO	0·03
P_2O_5	0·03
H_2O-	0·23
H_2O+	0·70
	100·55

	2	3	4
Quartz	31·3	35·5	33·3
Orthoclase	18·7	15·9	9·8
Plagioclase	27·2	35·2	35·3
Biotite	19·6	11·8	20·5
Muscovite	tr.	—	tr.
Cordierite	tr.	1·0	0·6
Sillimanite	tr.	tr.	—
Accessories	3·2	0·6	0·6

1. Gneissic granodiorite, Pretty Valley Dam Site (V. Biskupsky); 2. Gneissic granodiorite, Pretty Valley Dam Site; 3. Gneissic granodiorite, Pretty Valley; 4. Gneissic granodiorite, Cobungra.

Village, relatively large zircons are present; almandine after biotite, and sillimanite after quartz are also found in the granodiorite.

Varying amounts of shear, metasomatism, and recrystallization have been observed in this granodiorite. These are seen also in a number of smaller granodiorite stocks throughout the area. At Langford's Gap and at Rocky Valley Dam the plagioclase has been almost completely sericitized, with partial recrystallization of the sericite to muscovite. On Frying Pan Spur, and the Spion Kopje fall of Rocky Valley, similar features, together with some recrystallization of the quartz were noted.

Shearing is localized on well defined zones. Granulation is a reflection of minor shear, but the ultimate product is a mylonite (Beavis 1961). The principal effects of metasomatism have been bleaching, the introduction of secondary quartz, calcite sulphides, the replacement of ferromagnesians by clinozoisite, and the saussuritization of the felspars. Metasomatism has been most effective in and adjacent to shear zones. At Howman Dam Site, a typical rock has been observed. The biotite is bleached, and partly replaced by clinozoisite. The poikilitic felspars are saussuritized, and secondary quartz and pyrite are present. It is clear that at least two periods of metasomatism have occurred: the older, a quartz-sulphide metasomatism is probably to be dated with the final stages of Palaeozoic intrusion, and the younger, a calcite metasomatism, is of Tertiary (volcanic) age.

INTRUSIVES: BIG HILL QUARTZ DIORITE

The deep dissection of the quartz diorite of Big Hill has permitted an examination of the rock over a vertical distance of some 3,000 ft. The only distinction between the high and low level exposures, however, is the absence from the latter of the melanocratic schlieren which are typical of the high levels.

The most outstanding feature of the quartz diorite is the abundance of euhedral, frequently twinned crystals of green brown hornblende. Quartz occurs as anhedral pools. Plagioclase (An 40 –35) is the commonest constituent, occurring as large

TABLE 7

Analyses of Granodiorites

	1	2
SiO_2	65·00	65·50
Al_2O_3	19·33	14·75
Fe_2O_3	1·83	3·13
FeO	3·08	2·20
TiO_2	0·04	0·34
MnO	0·08	0·07
P_2O_5	0·04	0·13
CaO	3·28	3·28
MgO	1·60	1·06
Na_2O	1·35	3·80
K_2O	2·45	3·12
H_2O-	0·12	0·12
H_2O+	0·90	0·83
	100·16	99·33

Analyses: V. Biskupsky

	3	4	5	6	7	8	9
Quartz	38·4	25·5	29·8	32·5	41·9	24·7	26·1
Orthoclase	25·9	19·9	6·1	14·5	3·2	13·9	26·1
Plagioclase	21·6	43·3	49·1	37·4	26·5	38·5	31·2
Biotite	10·1	9·3	9·3	16·3	20·9	20·5	16·1
Muscovite	—	—	—	—	tr.	—	—
Hornblende	—	1·3	—	0·1	—	—	4·3
Epidote	tr.	—	1·1	tr.	3·2	tr.	tr.
Cordierite	—	—	—	—	1·1	—	—
Accessories	4·0	0·4	1·1	2·4	tr.	2·4	1·2

1. Granodiorite, McKay Cr.; 2. Granodiorite, No. 3 Tunnel; 3. Pink granodiorite, No. 3 Tunnel; 4. Grey ganodiorite, No. 3 Tunnel (Baker 1950); 5. Metasomatized granodiorite, Howman's Gap; 6. Pink-green granodiorite, No. 3 Tunnel (Baker op. cit.); 7. Granodiorite, No. 1 Power Station; 8. Granodiorite, Niggerheads; 9. Granodiorite, Bogong.

(3 mm) subhedral crystals, rarely zoned. Flakes of light brown biotite occur, all of which, in all sections examined, has been partially resorbed, and in a few cases has been replaced by magnetite. Ilmenite and leucoxene after ilmenite, zircon, apatite, magnetite and pyrite are accessory.

The schlieren of the high level exposures are of two types: one has a fine texture, with maximum crystal size 0·2 mm, the other is coarser, with crystals 0·5 mm in diameter. Both have much the same composition. Quartz is present in minor amounts. Orthoclase is rare, but frequently, poikilitic andesine, enclosing needles and flakes of hornblende and biotite, may constitute a greater proportion of the rock than in the normal quartz diorite. Biotite and hornblende, usually anhedral, are very common. Clinozoisite is secondary, and forms the core to some of the strongly zoned plagioclase.

At the contact between the quartz diorite and granodiorite a complex of relatively alkaline rocks occurs. Unfortunately the extremely deep weathering, and the consequent poor exposures did not permit field relationships to be studied. One type in the complex is a granite. Coarse textured, with crystal size 5 mm, this rock is composed of anhedral quartz, microcline, microcline-microperthite and orthoclase in excess of oligoclase, and frequently poikilitic biotite. Another type is a quartz syenite. The texture is medium, with microcline, microcline-microperthite, and orthoclase in excess of sodic oligoclase. Quartz, biotite and muscovite are minor constituents.

Table 8

Analyses of Quartz Diorites

	1
SiO_2	62·54
Al_2O_3	18·65
Fe_2O_3	2·06
FeO	3·32
TiO_2	0·47
MnO	0·05
P_2O_5	0·02
CaO	4·80
MgO	2·29
Na_2O	2·50
K_2O	2·22
H_2O-	0·14
H_2O+	0·47
	99·53

	2	3	4	5	6
Quartz	14·6	3·8	1·0	39·6	13·1
Orthoclase	6·9	1·3	3·2	tr.	1·5
Microcline	—	—	—	40·8	28·9
Microperthite	—	—	—	—	51·8
Plagioclase	46·4	64·5	67·6	7·7	0·3
Biotite	14·6	2·8	0·4	11·0	1·1
Muscovite	—	—	—	tr.	1·6
Hornblende	15·9	27·7	25·2	—	—
Epidote	tr.	—	—	—	1·0
Accessories	1·5	0·4	2·6	0·9	0·6

1. Quartz diorite, saddle between Big Hill and Bald Hill (V. Biskupsky); 2. Quartz diorite, Big Hill; 3. Fine textured schlieren, Big Hill; 4. Coarse textured schlieren, Big Hill; 5. Granite, Big Hill; 6. Quartz syenite, Big Hill.

Lamprophyre Dykes

The rocks of this group are chiefly lamprophyres, but also to be considered here are felspar porphyrites, monchiquites and some of the basaltic dykes which show affinities to the lamprophyres. Baker (1950) described those rocks of this group which were exposed in the No. 3 Tunnel as spessartites, camptospessartites, augite lamprohyres, camptonites and monchiquites. Thin seitions of 110 dykes have been examined, and Baker's nomenclature has been retained, with the recognition of the additional felspar porphyrite and microdiorite. Some types approach odinite and kersantite in composition; variation was considerable, however, and recognition of these types did not appear to be warranted. The intense metasomatism of many of the dykes prevented certain identification. Hornblende is the most important constituent of the dykes, being an essential in 70 of the specimens studied.

The spessartities have a panidiomorphic texture, and are strongly porphyritic. The phenocrysts, invariably euhedral, are up to 1·5 mm long, and are hornblende and andesine. The groundmass is composed of hornblende and andesine, with microcrystalline texture. Magnetite may be abundant. The felspar phenocrysts are frequently zoned, with the cores highly calcic. At No. 4 Power Station, one spessartite dyke has a chilled margin. The texture of the marginal rock is cryptocrystalline to microcrystalline, with some rare skeletal crystals of hornblende, and abundant magnetite. Xenocrysts of quartz have been partly absorbed by the dyke rock.

In the camptospessartites euhedral phenocrysts up to 2 mm long occur in a microcrystalline matrix. Most of this type examined showed advanced metasomatism; the phenocrysts of augite have been almost completely replaced by clinozoisite, but the brown hornblende phenocrysts are less affected. The felspar, originally labradorite, have been saussuritized. Any andesine present is restricted to the groundmass.

A dyke on Timm's Lookout is one of the few on the area which may be referred with certainty to the camptonites. The texture is hypidiomorphic microporphyritic, with microphenocrysts 0·6 mm long, of euhedral zoned augites, the cores titaniferous, and the outer zone diopsidic. The augite microphenocrysts are sometimes poikilitic with inclusions of ilmenite. Augite also occurs as subhedral crystals in the groundmass, together with laths of labradorite, and small flakes of biotite.

The felspar porphyrites have a panidiomorphic texture. The phenocrysts are oligoclase-andesine, often poikilitic, enclosing small flakes of green mica. The groundmass consists of euhedral to subhedral andesine, hornblende, magnetite and ilmenite. In some specimens from dykes at Clover Dam the hornblende occurs as glomerophenocrysts. A more acid type occurs on the summit of Mt Bogong. Euhedral phenocrysts of sericitized felspar are 1 mm long. Hornblende and euhedral quartz also form phenocrysts; the quartz sometimes has embayed margins, but otherwise there is no evidence of reaction between the quartz and the groundmass, and the quartz is no doubt primary. The groundmass is composed of felspar, chloritized hornblende, quartz, and iron ore.

The microdiorites are characterized by a fine equigranular to subequigranular texture. Laths of calcic andesine, and euhedral to subhedral hornblende and occasionally augite, are the essential constituents, with the andesine dominant. In one specimen from the No. 4 Head Race Tunnel the augite is dominant, while in another specimen from the same tunnel some biotite is present.

The basalt dykes, which are only tentatively correlated with the lamprophyres, have olivine and diopsidic augite with laths of labradorite as the essential constituents. The texture varies from microcrystalline to cryptocrystalline. Primary calcite is present, and some magnetite is accessory. The monchiquites have a microcrystalline subequigranular texture. Augite, usually diopsidic, but sometimes titaniferous, forms laths up to 0·5 mm long. Olivine is abundant and has been partially replaced by serpentine. Labradorite is a minor constituent, but magnetite is abundant.

Metasomatism has been active in all of the dykes examined. Where the dykes have been sheared, the metasomatic effects are extreme. The writer has not been able to confirm in general the observations of Baker (1950) that the dykes have not been sheared. The chief effects of metasomatism have been the saussuritization of the felspars, and frequently, the replacement of this material by clinozoisite. Clinozoisite has frequently replaced biotite, hornblende and augite, and secondary pyrite, chalcopyrite, magnetite, quartz, and calcite have been introduced.

Acid Dykes

Five types of acid dyke were recorded in the area: granodiorite aplite, microgranodiorite, granophyre, pegmatite, and granodiorite porphyrite. The granodiorite aplites have a fine saccharoidal texture, and are composed of quartz, oligoclase in excess of orthoclase, and rare biotite. On the summit of Mt Bogong, a type with abundant euhedral almandine was recorded. Secondary pyrite is sometimes present. The microgranodiorites are rare. These have almost the same composition as the granodiorites, but biotite seems to be reduced. The granophyres are biotite rich types, with the texture typically granophyric. Phenocrysts of biotite and oligoclase occur in a finely crystalline groundmass of quartz, orthoclase, biotite, and rare

TABLE 9

Analyses of Lamprophyre Dyke Rocks

	1	2
SiO_2	53·46	51·45
Al_2O_3	18·40	19·75
Fe_2O_3	2·76	0·72
FeO	5·52	5·80
TiO_2	1·19	0·95
MnO	0·08	0·08
P_2O_5	0·04	0·04
CaO	4·06	7·84
MgO	6·05	7·32
Na_2O	1·95	2·00
K_2O	1·68	1·71
H_2O-	0·56	0·07
H_2O+	3·36	1·45
	99·11	99·18

	3	4	5
Quartz	—	—	1·8
Orthoclase	4·8	tr.	1·8
Plagioclase	21·6	51·2	22·8
Biotite	—	—	1·8
Hornblende	8·9	tr.	64·5
Augite	—	41·1	—
Matrix	61·5	—	—
Accessories	3·2	7·7	3·7*

* Secondary calcite 3·6% also present.

1. Spessartite, Clover Dam (Analysis by V. Biskupsky); 2. Microdiorite, Beckraith Cr. (Analysis by Biskupsky); 3. Felspar porphyrite, Clover Dam; 4. Augite lamprophyre, Mossybank, Pretty Valley; 5. Spessartite, Clover Dam.

muscovite. In the granodiorite porphyrite phenocrysts of biotite and oligoclase occur in a groundmass of quartz, oligoclase-andesine, rare orthoclase and biotite. The pegmatites are very coarse grained. Intergrowths of quartz and orthoclase perthite are typical. Muscovite may be present, but biotite is always absent. Euhedral almandine and tourmaline may occur, and on Mt Bogong, one specimen contains tantalite.

CATACLASTIC ROCKS

The mylonites and cataclasites of the Kiewa area have already been described (Beavis 1961). These rocks are associated with the older faults of the area. Associated with many of the younger faults are incoherent cataclastic rocks, the most important of which are gouge, breccia, and fault conglomerate. Brecciated mylonite and cataclasite, due to renewed movement on old faults are not uncommon. The breccias consist of lens shaped fragments of varying dimensions, but generally with a maximum length of 6 in. These lenses are separated by thin seams of gouge up to 5 mm thick. The faces of the lenses are polished and slickensided. Little change has been noted in the composition of the rocks except that immediately adjacent to the faces, the felspars may be sericitized, and the micas 'smeared'. There is however a preferred orientation of the quartz crystals on the faces.

Fault conglomerate was observed only once. This was cut by the No. 4 Tail Race Tunnel over a length of 300 ft. The rock affected was a permeation gneiss intruded by lamprohyre dykes. Boulders of both gneiss and lamprophyre were recognized in the conglomerate. The boulders, up to 5 ft in diameter are well rounded, with the surfaces strongly slickensided. The matrix is black, very fine material. The smaller particles were monomineralic, often clay size, but particles greater than 1·17 mm were recognizable rock fragments. Secondary calcite had partially cemented the matrix.

The gouge contains a number of minerals, including chlorite, indicative of slow movement, with relatively low pressures and temperatures. The X-ray pattern of a gouge from Mt Beauty is shown on Table 10.

TABLE 10

X-ray Powder Pattern: Gouge

I (est.)	2	1	8	4	9	7	8	1	5	3	2	2	1
d (kx)	14·01	9·82	6·97	4·66	3·55	3·30	3·02	2·88	2·59	2·49	2·30	2·03	1·96

THE BOGONG VOLCANICS

BASALTS AND LIMBURGITES

The basaltic rocks are strikingly uniform in composition, with olivine basalts predominating. Basal flows are generally more basic, comprising limburgites and limburgitic basalts. Associated with the basalts are plugs and dykes of phonolite and tinguaite, and dolerite dykes.

RUINED CASTLE

The lower flows have a microporphyritic texture, with glomeroporphyritic texture locally developed. Flow structure is seen only at the top and base of the individual flows. Augite, olivine and labradorite occur as phenocrysts. The olivine, a forsteritic type, is frequently replaced by serpentine, or very rarely, by iddingsite. The augite is diopsidic, with $2V = 50°$, although some pale mauve augite with $2V = 60°$ also occurs. The augite is frequently twinned, sometimes zoned, and may be poikilitic. In one specimen reaction has occurred between analcite and augite to produce aegerine. Local limburgitic basalts have less felspar and a greater proportion of mauve augite. In these, halloysite and calcite occur sporadically.

In the upper flow, augite, olivine and labradorite occur as phenocrysts in a cryptocrystalline to glassy matrix. The olivine is sometimes replaced by iddingsite. Brown diopsidic augite is commoner than mauve augite, but the latter occurs more frequently than in the lower flows.

BASALT HILL

The basal flow is a black, non-vesicular limburgite, with olivine and zoned diopsidic augite as subhedral microphenocrysts in a microcrystalline groundmass of augite, olivine, and varying, but significant, amounts of labradorite. Analcite is present as an essential constituent. The middle and upper flows are olivine basalts, the essential difference between the two being the absence of augite from the matrix of the middle flow.

MT JIM-BUNDARRAH

Seven distinct flows, each separated by tuffs and lacustrine sediments, have been recognized. With the exception of the basal flow (flow 1) and localized sections of higher flows, all are olivine basalts. The limburgite of flow 1 outcrops around the margin of the outlier, with the best exposures near the Niggerheads and at Dibbin's Lookout. Phenocrysts of diopsidic augite, 2 mm long, and generally euhedral, are set in a matrix of augite, olivine and magnetite; minute laths of indeterminate felspar and grains of analcite are also found in the matrix.

The basalt of flow 2 is a dark coloured, non-vesicular rock, with laths of labradorite 0·75 mm long, abundant. Anhedral microphenocrysts of diopsidic augite have an outer zone of mauve augite. Olivine has been partly replaced by serpentine. The matrix is green in colour, and varies from cryptocrystalline to glassy. The basalt of flow 3 is similar, except that near the base of the flow, the augite is colourless, and is restricted to the matrix, while the olivine has been iddingsitized. Olivine is the only mineral in the basalt of flow 4 which occurs as phenocrysts. It may be replaced by iddingsite, but more commonly by serpentine. Limburgitic types are present in this flow. In flow 5, olivine occurs as subhedral phenocrysts, together with pale brown augite, showing hour glass structure. The augite tends to a glomeroporphyritic habit. The augite of flow 6 is similar, but in this flow, labradorite often constitutes the bulk of the phenocrysts. In the uppermost flow, flow 7, the felspar is restricted to the matrix.

The Young's Hut outlier has been intensely faulted. While certain correlation with a particular flow of the main outlier is impossible, it has affinities with flow 2. Phenocrysts of diopsidic augite with an outer zone of mauve augite are 1 mm long, while microphenocrysts of titanaugite are abundant. The olivine has been replaced completely by iddingsite. Labradorite is restricted to the matrix.

MT FAINTER

This basalt has a microporphyritic texture, with olivine the only mineral occurring as microphenocrysts; these are subhedral, and up to 0·75 mm long. Most are unaltered, but some are partially serpentinized. The augite is diopsidic, and forms laths, the orientation of which impart a flow structure to the rock. A little glass is present in the matrix.

MT LOCH

Euhedral, frequently twinned phenocrysts of augite are 2 mm long, with a tendency for the augite to have a glomeroporphyritic habit. Olivine, with some serpentine along the cleavage planes also occurs as phenocrysts. Iddingsite after olivine is rare. The matrix is composed of augite, olivine, magnetite, labradorite, and brown glass.

ROPER'S LOOKOUT

The basalt here is notable for the xenocrysts of quartz, and the poor development of augite. It is fine grained, rarely glassy, with microphenocrysts of olivine in a groundmass of olivine, labradorite, and magnetite. In the vesicles of the scoria of this plug, natrolite and halloysite occur.

ROCKY CREEK

Intense alteration of the basalt of this neck makes determination of the original constituents difficult. The texture is porphyritic, with the original olivine phenocrysts now replaced by serpentine. The only mineral not altered is the diopsidic augite. The felspars have been replaced by a fine, clay like mineral. Calcite and analcite fill the numerous vesicles.

DOLERITE DYKES

Dolerite dykes, tentatively correlated with the basalts are exposed more or less uniformly throughout the area. They have a subequigranular, ophitic texture, with intergrowth of laths of labradorite, and euhedra of strongly pleochroic titanaugite. Analcite and ilmenite are essential constituents. Primary calcite has reacted to form ferrocalcite, a green fibrous mineral. One dolerite from the No. 4 Head Race Tunnel contains significant amounts of serpentinized olivine; in this rock the laths of felspar contain needles of aragonite.

ALKALINE ROCKS

Two tinguaite dykes were mapped: one on Timm's Lookout (Crohn 1949), and one in Big R. The texture is microporphyritic, with subhedral phenocrysts of alkali felspar 1 mm in diameter. Aegirine is restricted to the groundmass as needles and minute equidimensional crystals. In some sections, alteration has been intense, with the felspar sericitized, and the aegirine chloritized. Calcite has replaced the little nepheline which was originally present.

The phonolite of Mt Smythe is a dark coloured, dense, microporphyritic rock. Orthoclase occurs as subhedral phenocrysts and as 'streaks' of microcrystalline aggregates. Nepheline forms euhedral phenocrysts, and also occurs as laths in the matrix. Radiating aggregates of aegirine are common. The matrix is cryptocrystalline, and cloudy due to alteration.

Analyses of volcanic rocks are shown on Table 11. In addition to the chemical analyses, many modal analyses were completed. These showed a high proportion of matrix, and were of little value. The main conclusion drawn from the modal analyses (Beavis 1960) were that magnetite and olivine were more abundant near the bases of flows, but not appreciably so. The modal evidence was of no value in assessing the importance of oxidation processes at the surface and base of flows, nor in correlating the flows of one outlier with those of another.

TABLE 11

Chemical Analyses of Volcanic Rocks

	1	2	3	4	5	6
SiO_2	59·22	46·90	46·59	46·85	44·22	45·03
Al_2O_3	21·36	17·89	17·64	17·75	19·00	16·05
Fe_2O_3	2·86	0·06	0·06	0·12	1·75	1·41
FeO	0·32	8·10	7·92	8·08	7·20	7·56
TiO_2	—	1·58	1·42	1·40	1·48	1·65
MnO	0·11	0·10	0·10	0·09	0·68	0·09
P_2O_5	0·02	0·08	0·05	0·07	0·05	0·22
CaO	1·25	9·26	9·14	9·19	6·93	9·36
MgO	tr.	9·63	9·90	9·84	5·50	12·99
Na_2O	4·60	2·35	2·15	2·09	1·65	1·70
K_2O	4·32	1·84	1·54	1·75	1·06	1·34
H_2O-	0·65	0·38	2·20	0·70	3·00	0·62
H_2O+	4·85	1·54	0·45	1·60	7·62	1·48
	99·56	99·79	99·20	99·53	99·54	99·50

Analyses: V. Biskupsky

1. Phonolite, Mt Smythe; 2. Basalt, Ruined Castle; 3. Basalt, Mt Jim; 4. Basalt, Basalt Hill; 5. Dolerite, No. 4 Head Race Tunnel; 5. Limburgite, Dibbin's Lookout.

PETROFABRIC ANALYSES

A total of 50 petrofabric analyses of greywacke, schist, permeation gneiss, gneissic granodiorite, granodiorite and mylonite have been made, of which some have previously been discussed (Beavis 1961). For each rock, both quartz and mica fabrics were examined where possible. The petrofabric studies were aimed at supplementing other data for the petrogenic and structural research. The analyses are shown on Fig. 4.


c
b
a
b
c
d
e
f
g
h
i
j
N
S1
S2
S3
S4
k
l
m
n

A single macrolineation is present in the greywacke (b//B) and is horizontal. The infrequency of mica in the greywacke restricted the analysis to quartz. The quartz diagram, Fig. 4a, shows two well marked features: statistical maxima for the c axes of the quartz lying on *h0l* planes, more or less symmetrically disposed about *ab*, as well as the development of a partial girdle.

In the schists, lineation is developed to varying degrees. It is most prominent in the knotted schists where it is formed by the long axes of the knots on the weathered surface. It is least well developed in the low grade schists. An important aspect of the fabric of the schists is the lack of any but local deformation. The biotite diagrams for both schists examined have maxima in *c*, the biotite lying in the plane of the foliation. The three quartz fabrics show some differences. The low grade schist shows a partial *ab* girdle for the c axes, as well as two strong and one weak point maxima about *a*. The knotted schist shows an even less complete *ab* girdle, and a single point maximum. In the quartz schist, a strong *ac* girdle is present, with a maximum in *a* and two point maxima, one strong, one weak, on either side of the *ab* plane, i.e. on *0kl* planes.

The quartz diagrams show no clear evidence of a tectonite orientation, and it seems unlikely that the orientation of either the biotite or the quartz is due to deforming movements either during or after their recrystallization. The fabric indicates a crystallization schistosity, the orientation of the mica being a mimetic emphasis of a pre-recrystallization *s* plane. As pointed out by Knopf and Ingerson (1938) the crystallization in this fabric does not create *s* planes by changing the shape of pre-existing grains; it merely emphasizes an *s* plane that is already present. This idea also finds support in the field evidence that the foliation of the schists is parallel to the original bedding of the sediments, and that the recrystallization was mimetic.

Two specimens of permeation gneiss were examined: in both lineation was poorly developed. One from Clover Dam was also poorly foliated, but the other, from the No. 4 Head Race Tunnel showed a strong foliation and banding. In both cases, the biotite diagrams show maxima in *c*, and agree closely with the biotite fabrics of

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FIG. 4—Petrofabric Analyses.

a. 200 c axes of quartz, greywacke, Mt St Bernard. Contours 8-7-6-5-4-3-3-2-1% per 1% unit area.
b. Poles to 110 cleavage planes in biotite, low grade schist, Cobungra Gap. Contours 11-9-7-5-3-1%.
c. 212 c axes of quartz, same specimen as b. Contours 6-5-4-3-2-1%.
d. 287 c axes of quartz, quartz schist, Mt Nelse. Contours 5-4-3-2-1%.
e. Poles to 200 cleavage planes in biotite, knotted schist, Mt Nelse. Contours 15-10-5-4-3-2-1%.
f. 179 c axes of quartz, same specimen as e. Contours 5-4-3-2-1%.
g. Poles to 200 cleavage planes in biotite, permeation gneiss, Clover Dam. Contours 10-8-6-4-2%.
h. 103 c axes of quartz, same specimen as g. Contours 7-5-3-2-1%.
i. Poles to 200 cleavage planes in biotite, permeation gneiss, No. 4 Head Race Tunnel. Contours 10-8-6-4-2%.
j. 300 c axes of quartz. Same specimen as i. Contours 5-4-3-2-1%.
k. Poles to 300 cleavage planes in biotite, gneissic granodiorite, Pretty Valley. Contours 6-4-3-2-1%.
l. 187 c axes of quartz, same specimen as k. Contours 7-5-4-3-2-1%.
m. Poles to 300 cleavage planes in biotite, granodiorite, No. 1 Power Station, Contours 10-8-6-4-2%.
n. 200 c axes of quartz, same specimen as m. Contours 6-5-4-3-2-1%.

the schists. The quartz diagrams both show *ab* girdles, the girdle for the well foliated gneiss being more fully developed than that of the weakly foliated rock. Concentrations within these girdles occur in, or close to *a* and *b* of the fabric. As in the case of the schists, a non-tectonite fabric is indicated, the girdle here indicating the orienting influence of a set of parallel planes in which no one direction controls the movement. In this type of fabric, the planar surface does not control the direction of growth, nor actively guide the course of deformation, but acts passively by furnishing surfaces along which solutions were able to move freely. In such fabrics, if the solutions are free to move with equal ease in all directions within the controlling surfaces, the diagrams show, as in the present case, girdles parallel to the planes of maximum ease of movement. A criterion for such girdles is that they are normal to *c* of the fabric, rather than to *a* or *b* as in the case of tectonites.

In the hand specimen, only one *s* plane is visible in the gneissic granodiorite (s_1 of Fig. 4k). The biotite diagram indicates four *s* planes, however, all more or less equally developed. The interpretation of the quartz diagram is difficult, but there appears to be a tendency to girdle development. On the evidence of the fabric, the most important orienting mechanism seems to have been shearing stress. This is discussed more fully later in the paper.

Except locally, no macrofoliation was observed in the granodiorite. The study of a single set of sections from the No. 1 Power Station, showed girdles in the biotite with strong point maxima, suggesting the presence of three *s* planes, two of which are vertical, and one with a steep easterly dip. The possibility that one of these may represent primary flow cannot be excluded. Comparison of the diagrams with those of the macrofracture patterns show that there is apparently no relationship between the two. As in the case of the gneissic granodiorite, the quartz diagrams are difficult to interpret; comparison with the biotite diagrams is the only basis for study, possibly indicating that the quartz maxima lie on *h0l* planes which can be related to the *s* planes of the biotite diagrams. This suggests the orienting influence of shearing, and while not a satisfactory explanation is the one which best fits the data.

PETROGENESIS

The field and petrographic evidence indicate a close genetic relationship between the schists and the permeation gneiss. Joplin (1952) recognized six stages in the metamorphism and granitization of the Cooma Complex: regional metamorphism; superimposed thermal metamorphism; permeation, without addition from a magma; addition from an attentuated magma; formation of a potassic wave front; and finally, the injection of the magma as concordant intrusions. Tattam (1929) noted the essentially thermal nature of the metamorphism. The parallelism of bedding and foliation at Kiewa, and the absence of axial plane foliation indicate the importance of non-dynamical recrystalization (cf. Fairbairn 1935). The mimetic fabric of the schists is further evidence of non-dynamical recrystallization.

Kyanite and andalusite zones are absent, any andalusite being restricted to the contact zones of later intrusions. The relatively early appearance of sillimanite is also due to later intrusions. The apparently retrograde metamorphism indicated by the pinitization of cordierite in the zone of knotted schists is significant. It is almost certainly the result of reaction with aqueo-potassic material (Tattam 1929) and is to be regarded as evidence of the potassic wave front postulated by Joplin at Cooma.

Examination of the analyses presented earlier, as well as those presented by Tattam (op. cit.) show little significant addition during metamorphism. The composition of the permeation gneisses is essentially granitic, and it seems probable that the gneiss originated in the soaking of the schists with granitic magma. The pegmatitic lenses of the gneiss are also to be regarded as representing magmatic addition. There is evidence at Kiewa that most of Joplin's stages can be recognized. There is no evidence of the final stage of concordant intrusion. What Joplin meant by 'permeation without addition' is difficult to understand, and at Kiewa, there is certainly no evidence of such a process.

The field evidence has shown that the gneissic granodiorite is the oldest of the intrusives, but the age difference between this rock and the non-foliated granodiorite is very small. The marginal features of the gneissic granodiorite as well as the foliation, suggest comparison with the gneiss of the Scottish Highlands described by Barrow (1893). Barrow concluded that the gneissic structure was due to shearing stress applied at the late magmatic stage, the stress also resulting in the transfer of the still liquid part of the magma to the margins of the mass where it crystallized as dykes. The petrofabric evidence at Kiewa indicates shear, and, with the complete absence of strain in the minerals, it seems clear that the shearing stress was operative at a stage when the crystals were capable of dimensional orientation, but without any deformation of the crystal lattices; i.e. at a stage when part of the magma was still in the liquid condition. This tends to be supported by the dissimilarity between the biotite and quartz fabrics, particularly if the crystallization of the quartz was not completed until after the cessation of shear.

The macrofoliation of the gneissic granodiorite corresponds to one of the directions of shearing of the Bowning deformation. The parallelism of the dykes and schist rafts to the foliation of the gneiss also suggests shear at the time of the intrusion of the mass. Consideration of the microfabric shows four *s* planes, one of which is parallel to the macrofoliation. If we consider the case of the magma in a plastic state, confined between two relatively rough walls, an analogy can be drawn with the ideal case of a plastic fluid confined between rough plates which are approaching each other due to a compressive stress (Fig. 5).

FIG. 5—Development of foliation in gneissic granodiorite.

Jaeger (1956) gives the differential equations to the planes of slip developed in the fluid under these conditions, and these planes are shown in Fig. 5. Superimposed on the diagram are the *s* planes of the gneissic granodiorite. The orientation of the compressive stress in Fig. 5 is that of the Bowning Orogeny. It can be seen that the *s* planes of the gneissic grandodiorite are represented by the slip planes of the ideal case. The foliation of the gneissic granodiorite may be regarded therefore as due to shear within the partially crystallized magma, resulting from a compression on the walls of the magma.

Variations in the non-foliated granodiorites are considerable. Such variations appear largely, but not solely, to be due to shear and metasomatism. Where normal intrusive contacts could be studied, there was evidence of local contamination. Apart from this, there was noted a marked increase in the proportion of hornblende towards the northern (and deeper) sections of the East Kiewa granodiorite. The aplites and pegmatites associated with the granodiorites are to be regarded as late magmatic phases. That the granodiorites are normal intrusive types is certain; no evidence to suggest granitization was observed.

The Big Hill quartz diorite differs from other rocks of this type described by Edwards (1939) from North Eastern Victoria, in the total absence of pyroxenes. Edwards postulated a two pyroxene magma with, initially, two immiscible pyroxenes, diopsidic augite and hypersthene, crystallizing out. At a later stage, a single hornblende crytallized out in place of the pyroxenes, and by a discontinuous reaction, the two pyroxenes were replaced by hornblende. The quartz diorite of Granite Flat has green brown hornblende crystals enclosing colourless augite and hypersthene. Some of the melanocratic lamprophyre dykes at Kiewa show this feature, except that the enclosed pyroxene is invariably augite $2V = 50°$. If Edwards's idea is accepted, then the Big Hill quartz diorite is to be regarded as the final product of the differentiation process.

Edwards relates the intrusion of the quartz diorites with the granodiorites as well as with the extrusion of acid lavas in Eastern Victoria. This idea cannot be supported on the evidence from Kiewa. Highly acid and alkaline differentiates are rare at Kiewa, being restricted to small marginal granites and syenites. The lamprophyres are almost certainly comagmatic with the quartz diorite, and are basic differentiates of the quartz diorite magma.

The hornblende rich schlieren which are restricted to the higher levels, show no evidence of origin from assimilated gneiss or other older rocks in the area, and are obviously primary flow structures. The present exposed upper surface of the intrusion, on this evidence, is therefore close to the original roof.

The mineralogy of the basalts and of the related alkaline rocks is remarkably uniform, and demonstrates the derivation of the lavas from an olivine basalt magma. Differentiation of the basalt magma proceeded normally to the late stages, when large volumes of lime and iron carbonates were released. These soaked the tuffs, Tertiary sediments, the more pervious basalts, and shear zones in the older crystalline rocks with calcite and siderite.

The possibility that some at least of the melanocratic dykes of the area were related to the basalts was investigated. The basalt and monchiquite dykes have affinities with both the basalts and the quartz diorites. The dolerites, however, are certainly to be correlated with the basalts, since dykes of this type intrude. Jurassic rocks in South Gippsland (Edwards 1934). Titaniferous augite is the characteristic pyroxene of the three dyke rocks, while the augite of the lamprophyres is generally diopsidic. The titanaugite is to be regarded, however, more as an indicator of temperature conditions in the magma chamber, than as evidence of consanguinity with one or other of the two magmas.

Structural Geology

The data on which the structural work has been based included some 8,000 field contact measurements. The application of statistical techniques, necessary because of the monotonous lithology, was possible, therefore, with little chance of error due to inadequate observation. Compensation for poor surface exposures was found in the detailed sections provided in the 6 miles of tunnel constructed during the period in which the area was studied.

FOLDING

Bedding is the only strong *s* surface uniformly developed in the Upper Ordovician sediments in the area; the cleavage of the slates is usually, but not invariably,

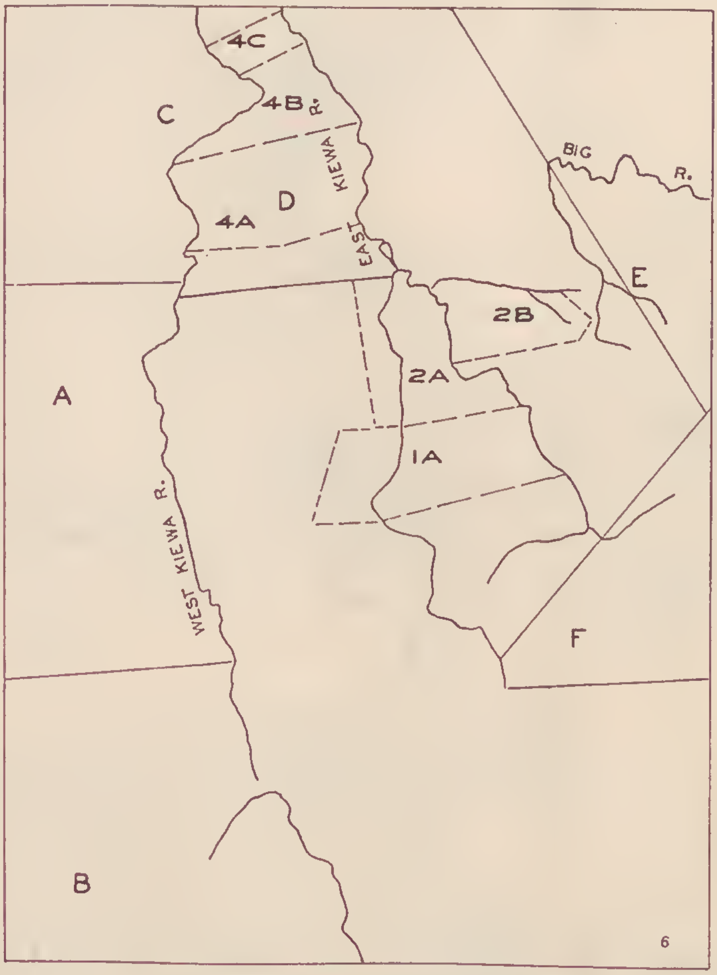
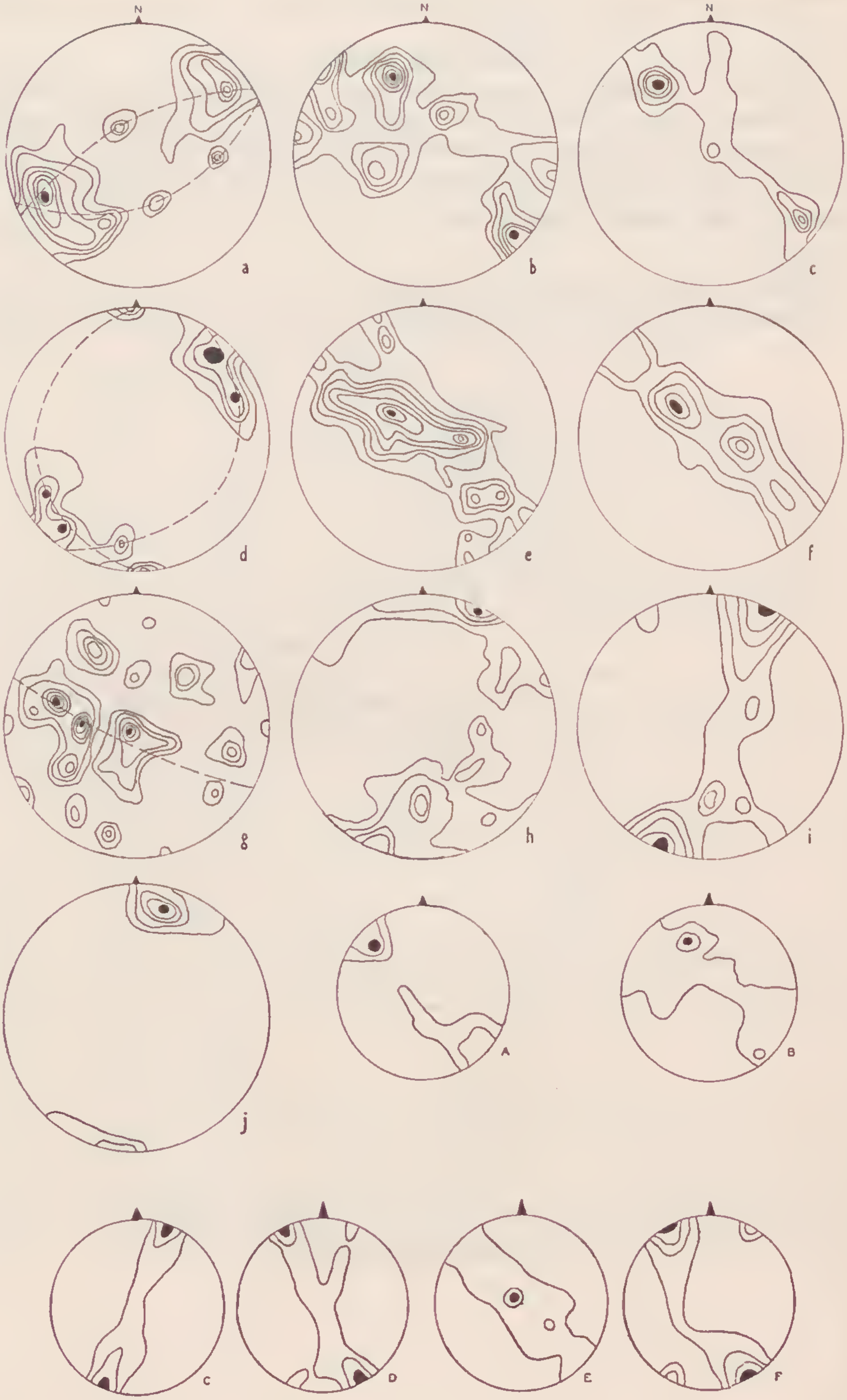


FIG. 6—Index Map, Structural Studies.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parallel to the bedding. In the SW. sector, the trend of the fold axes is uniformly N.40°W. to N.60°W., but towards the N., a strong westerly swing occurs. Dip of the beds is predominantly N.-easterly, but S.-westerly dips are not infrequent. Only minor folds were recorded, with axes at intervals of 400 to 500 ft. The folds are characteristically sharp, but not acute. Lineation parallel to the fold axes is strongly developed as minute puckers on the bedding planes. The lineation has dominant plunge 35°NW., although plunge 15°SE. is also important.

The field impression that N.-easterly dips predominate is confirmed by the π diagram of Fig. 7a. This diagram may be interpreted as suggesting that the sediments mapped occupy an E.-dipping limb of an anticlinorium or synclinorium, a type of folding characteristic of the lower Palaeozoic beds which have been mapped in detail further to the W. Alternatively, the beds may be regarded as the limb of the main Kiewa Anticline, the dominant fold structure of the area. The β diagram and the B diagram (Fig. 7b,c) show two distinct maxima, with $\beta_1 = B_1$ and $\beta_2 = B_2$. Several interpretations are possible. The first, in accordance with Sander's ideas, is that there have been two foldings. However, the diagrams suggest, rather, either a doming structure, with reversal of plunge, or 'splitting' of folds similar to that described by Thomas (1953) at Chewton. If the idea of doming is valid, more horizontal β axes would be expected than were actually recorded; moreover, doming would be expected to produce β maxima normal to those recorded. Detailed field mapping in areas where exposures were suitable suggested that the concept of the splitting folds is the more acceptable.

In the Mt St Bernard-Mt Blowhard area, the splitting of folds may be observed (Fig. 8a). Small folds may be seen to develop on the limbs of the larger folds, the dimensions of the small folds increasing along the strike. The first sign of development is the terracing of the limbs, these terraces passing into recognizable anticlines and synclines within distances of as low as 50 ft.

The nature of the sediments, together with a consideration of the geological history of the area, suggest that the sediments, once folded, would at the time of later deformations, be in a more or less brittle condition. These rocks would then not be expected to undergo further folding, and deformation by fracture during the later orogenies was more likely. Within the sedimentary belt mapped, failure by fracture is seen adjacent to the West Kiewa Thrust and the Tawonga Fault. In the former case post-folding deformation is seen in shear zones more or less parallel to the fault, and to the fold axes, the shears increasing in frequency and intensity easterly from Mt St Bernard. In the case of the Tawonga Fault the fold axes have

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Fig. 7—Statistical Diagrams of Folding.

a. π Diagram, Ordovician Sediments. 356 points, contours 8-6-5-4-3-2-1%.
b. β Diagram, Ordovician Sediments. Contours 7-6-5-4-3-2-1%.
c. B Diagram, Ordovician Sediments. 118 B axes, contours 5-4-3-2-1%.
d. π Diagram, Schists. 268 points, contours 4-3-2-1%.
e. β Diagram, Schists. Contours 8-7-6-5-4-3-2-1%.
f. B Diagram, Schists. 260 B axes, contours 5-4-3-2-1%.
g. π Diagram, Permeation Gneiss. 600 points, contours 6-5-4-3-2-1%.
h. β Diagram, Permeation Gneiss. Contours 5-4-3-2-1%.
i. B Diagram, Permeation Gneiss. 210 B axes, contours 5-4-3-2-1%.
j. Poles to 159 foliation planes, gneissic granodiorite, Pretty Valley. Contours 30-10-5-2-1%.
A.–F. β Diagrams of sub areas A–F. of Fig. 6. Contours A–E 5-3-1%, F 7-5-3-1%.

been dragged to the W., but there is no variation in the plunge of the fold axes. Crushing of the sediments has occurred adjacent to the fault.

E. of the Kiewa area the Ordovician sediments have been only cursorily examined. In the Mitta Mitta Valley the folding tends to be closer and sharper than in the Kiewa Valley, while intense crumpling is not uncommon. The fold axes at Mitta Mitta have very steep southerly plunge.

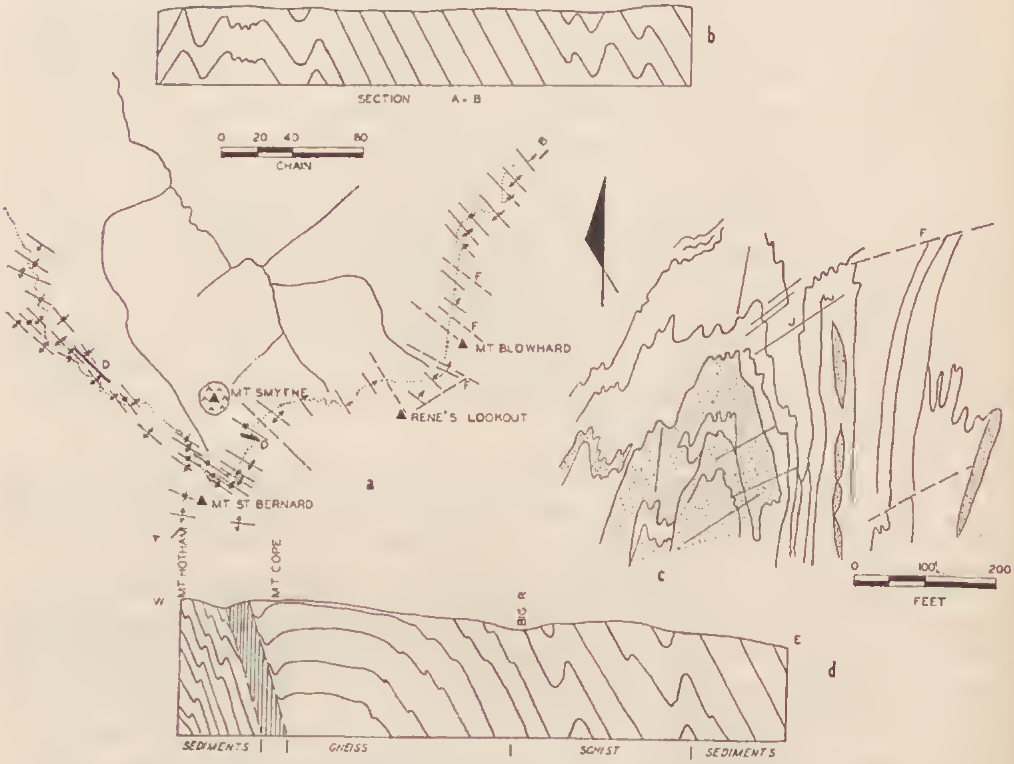

FIG. 8—Folding of Palaeozoic Rocks, Kiewa.

a. Map showing folding of Ordovician sediments, Mt St Bernard.
b. Section A–B of Fig. 8a.
c. Folding of Permeation gneiss, Bogong.
d. Regional cross section showing Kiewa Anticline.

Both the field observations and the study of thin sections have shown that the foliation of the schists is parallel to the original bedding, a feature previously noted by Crohn. Lineation is usually well developed as corrugations on the foliation planes and by the dimensional orientation of mineral crystals and nodules. Folding of the schists seems to be broader than that of the sediments. The statistical geometry of the folding in the schists is shown on Fig. 7 d-f. S.-westerly dips are more important than N.-easterly. The β and B diagrams have features comparable to those of the diagrams for the sediments. Plunge of the fold axes, however, is steeper.

In the valley of Camp Cr., Mt Bogong, local isoclinal folding of the schists was observed, and adjacent to the Tawonga Fault at Mt Beauty, the schists are crumpled. Apart from these purely local features, the folding of the schists is comparable to that of the Ordovician sediments, and in view of the nature of the metamorphism, any marked differences would be unexpected.

Studies of the foliation of the permeation gneiss have been based on the assumption that the foliation represents the bedding of the original sediments, an assumption made by Spencer (1959) in mapping comparable gneisses in U.S.A. At Kiewa, where the normal transition from schist to permeation gneiss could be studied, foliation was continuous through the transition, thus giving some justification for the assumption, which is supported also by the very obvious sedimentary structures in the gneiss. Foliation and banding are always reasonably strong in the permeation gneiss, but lineation is not always apparent. When it is present, lineation is due to the orientation of inequant mineral crystals, usually sillimanite. Fine, often complex folding (Fig. 8c), is typical, but ptygmatic folding was only rarely seen. One of the most important aspects of the folding in the gneiss is the dominance of sub-horizontal foliation, a feature noted by Crohn (1949), who, however, made no attempt to assess the significance of this.

Fig. 7g-i illustrates the statistical geometry of the folding of the permeation gneiss. The π diagram illustrates the wide variety of attitudes in the foliation, and emphasizes the importance of the horizontal foliation. There is a single B maximum corresponding to the β maximum. The interesting point is that, in strong contrast to the sediments and to the schists, plunge of the fold axes is zero, and moreover, there is a strong easterly swing in the trend of the axes, which is a departure from the trend not only at Kiewa, but in the complex as a whole. This variation in trend could be due to one or more of several features: rotation of the whole of the central block at Kiewa, or to rotation of a single block from which the excess of field measurements could weight the result. In compiling the diagrams for the gneiss, between 65% and 70% of the measurements were taken in the N. part of the area. The whole of the mapped area was divided, therefore, into sub-areas, and β diagrams prepared for those areas for which at least 200 readings were available. These are shown on Fig. 7 A-F, where it can be seen that with the exception of the block (Area C) bounded by the Tawonga and Big Hill Faults, the trends of the axes are consistently NNW. It is apparent therefore that the regional β diagram has been influenced by the great number of measurements from this subarea, in which rotation has occurred. In this subarea, the older joints, faults, and lamprophyre dykes also show an easterly rotation. Such rotation was probably not simply in the horizontal plane, but also involved rotation in the vertical plane since there is a marked flattering in the plunge of the fold axes.

Synthesis of the regional folding cannot be attempted yet, but the study of the fold geometry at Kiewa has enabled an assessment of the fold pattern of this area to be made. N. of Kiewa, Tattam (op. cit.) showed that the dip of the sediments on both sides of the metamorphic belt is westerly, and this was interpreted as indicative of overfolding to the E. of the acutely folded sediments. At Kiewa, the sediments have a dominantly easterly dip, while the statistical evidence suggests an areal trend of the fold axes to the NNW., with gentle northerly plunge. Fig. 8d, a cross section of the Kiewa area, is an interpretation of the folding. The structure is pictured as a large, open anticline, the core of which has been migmatized. The W. limb of the fold is pictured as being sheared through on the West Kiewa Thrust, either at a late stage of the folding, or immediately post-dating the folding. The structure as a whole has a NN.-westerly plunge, although there is some general suggestion in the trend lines of the foliation (Fig. 2) that there is locally a reversal of plunge to the S.

This concept of the folding tends to regard the Ordovician sediments of the W. belt as occurring in the W. limb of the Kiewa Anticline, rather than as a limb of an entirely separate structure. If these sediments are part of the Kiewa Anticline, then this structure is almost certainly overturned to the W. Such an interpretation accounts for the predominance of easterly dips, as well as explaining the importance of the horizontal foliation in the permeation gneiss. This structure is to be regarded as the result of the development of tangential stresses from the E. during the Benambran Orogeny.

The difference in the structure at Kiewa and that further N. described by Tattam is difficult to explain, since in the former, overturning is to the W., and in the latter, to the E. It is possible that Tattam, whose prime interest was petrological, overlooked some structural data, and, at this stage, pending a structural re-examination of the area to the N., no explanation of the differences can be offered.

With the exception of the gneissic granodiorite, the intrusive rocks show only very localized and weak foliation. The foliation of the gneissic granodiorite is strong, and has a uniform attitude throughout both masses. Strike is a few degrees N. of W., with dip steeply S. (Fig. 7j). It is interesting to note that this is parallel to one of the main joint sets in the rock, and almost normal to the other joint set. The foliation of this granodiorite, as shown earlier, was the result of a stress acting from the NE. during the Bowning Orogeny. Normal granodiorites subjected to post intrusive shear have a weak foliation, generally parallel to some major shear zone cutting the rock.

FAULTING

The field work disclosed almost 1,000 faults; of these, only a few have any significance in the gross geology of the area. The faults were studied in two ways: field study of the larger and more important structures, and statistical study of the attitudes of all the faults recorded. Petrological and petrofabric studies of the cataclastic rocks (Beavis 1961) were used to determine the physical conditions of faulting.

Generally the faults are marked by crush zones of varying thickness. Average thickness was 10 ft, with extremes of less than 1 inch, and more than 1 mile. Determination of the displacement along the faults was always difficult, and sometimes impossible. Similarly, dating the fault movement was often difficult, but as a result of the statistical work, indirect methods were developed to date at least the original movement on some of the more important. Of the faults studied, both strike slip (wrench) and thrusts were recognized. Normal faults are rare.

One of the most important of the faults, the Tawonga, has been described (Beavis 1960). This a wrench fault of Palaeozoic age, on which Tertiary movement, in part low angle thrusting, occurred. Of equal importance is the West Kiewa Thrust. Howitt (1892) examined the metamorphic boundary in the Upper Dargo Valley, and recognized a normal transition, though commenting on the cataclastic nature of the schists. Crohn (op. cit.) commented on the asymmetry of the schist belts at Kiewa. Crohn offered no explanation of this asymmetry.

S. of Mt Beauty, the W. margin of the metamorphic complex is marked by a physiographic lineament occupied by the West Kiewa, Upper Cobungra, and Upper Dargo R. This lineament suggested a structural control for the W. boundary of the complex, now established between Mt Beauty on the West Kiewa, and Mayford, on the Dargo. The lineament is occupied by a zone of mylonite up to 1 mile in outcrop width. On the W. of this zone, the Ordovician sediments have steep dips parallel to the foliation of the mylonite of the zone, and are broken by strike shears, which decrease in frequency away from (to the W.) the zone. To the E., the permeation gneiss abuts against the mylonite, the foliation of the gneiss being parallel to that of the mylonite. The foliation of the mylonite dips consistently 70° to 80° E., with strike N.15°-20° W., parallel to the walls of the zone.

The schist described by Howitt from the Upper Dargo is a southerly continuation of this mylonite. To the N., the mylonite is terminated by the Tawonga Fault, and so far, no direct evidence of the West Kiewa Thrust has been found N. of Mt Beauty. Thomas (1949) suggested that the lower Kiewa R. may have developed on a major fault, and it is possible that mylonite may occur beneath the alluvium of the valley floor. This idea finds some support in the shearing of the low grade schists, and the occurrence of myonite lenses, on the W. margin of the alluvium, and the gross difference in grade of the metamorphic rocks on either side of the alluvium.

The mylonite belt of the West Kiewa Valley could have resulted only from intense shearing. It is considered that this belt has developed in association with a high angle thrust, the West Kiewa Thrust. The thrusting post dated, or was contemporaneous with the folding, and pre-dated the intrusion of the granodiorites, since the Niggerheads Granodiorite intruded the mylonite. The Thrust is therefore of probable Benambran age. Renewed movement is indicated by the brecciation of the mylonites at Cobungra Gap.

A feature of considerable interest is the probable control of igneous intrusion exerted by the West Kiewa Thrust. E. of the Thrust, a number of intrusions have been mapped, whereas to the W., only a few, large, intrusive masses have been recorded. The main significance of this fault, however, is that it forms, at least in the S. sector, the W. boundary of the metamorphic complex. The nature of the boundary N. of the Tawonga Fault requires further study.

The Nelse Fault, represented in the field by a belt of mylonite with outcrop width of 50 ft, has been traced over a length along the strike of 14 miles, from Big R., S. of Glen Wills, to its termination against Spion Kopje Fault, in Spion Kopje Cr. One of the most important aspects of this fault is the displacement along it to the SE., by some 8 miles, the schist-permeation gneiss transition. In effect, in the area examined, the Nelse Fault forms the S. boundary of the schist belt.

Physiographically, the fault forms a strong lineament, with a number of small streams developed along the crush zone. Over the length mapped, the fault is almost perfectly straight, with strike N.45°W. Dip is vertical. Fabric studies of the mylonite (Beavis 1961) showed the importance of shearing stress in the faulting, and so far as can be judged from such evidence as lineation, movement was purely strike slip. Movement does not appear to have recurred; brecciation of the mylonite, typical of many of the older faults, is absent. In age, it is older than the Spion Kopje Fault against which it is apparently terminated to the NW. It may post date granitic intrusion, but this is uncertain. N. of the Spion Kopje Fault the Nelse Fault has not been certainly identified, although the fault bounding the NE. extremity of the East Kiewa Granodiorite, may be an extension.

A zone of brecciated mylonite, ultramylonite, and cataclasite up to 60 ft thick, is associated with the Spion Kopje Fault. This fault has been traced from Bogong Village easterly to Duane's Spur on the Big R. The physiographic influence of the fault is particularly strong, Spion Kopje Cr. occupying the crush zone for almost the entire length of the stream. The average strike of the fault is E.-W., with average dip vertical, but there are marked variations in both strike and dip. Displacement along the fault does not appear to have been great, since the E. margin of the East Kiewa Grandodiorite has been displaced less than ½ mile where it has been cut by the fault. On the other hand, the granodiorite cut by the Spion Kopje Fault in Tiger Snake Gap, Big R., has not been matched S. of the fault.

The age of the Spion Kopje Fault is possibly Bowning, since its trend corresponds with one of the statistical trends of shears developed by this orogeny. Later movement occurred, with brecciation of the older cataclastic rocks. The age of the latter movement is unknown, but it may have been that of the late movement on the Tawonga Fault.

One of the best exposures of the Bogong Fault, which has been traced from Little Bogong to Bald Hill, a distance of 8 miles, is seen where it crosses the spur rising to Mt Arthur S. of Bogong Cr. saddle. Here, mylonitized and brecciated gneiss is exposed over a width of more than 200 ft. The strike varies, but is generally NE. Dip is vertical. It is to be noted that the Bogong Fault forms the NW. boundary of the East Kiewa granodiorite, and the SE. boundary of the Big Hill quartz diorite. If a sinistral strike slip of 2 miles is assumed, it is seen that the two rock masses could originally have been in contact, suggesting that possibly the quartz diorite was intrusive into the granodiorite. Unfortunately, any contact phenomena which might give credence to this hypothesis are absent, although it is possible that these were destroyed during mylonitization. At the margin of the granodiorite there are a few poor exposures of a rock very rich in hornblende, and these may represent remnants

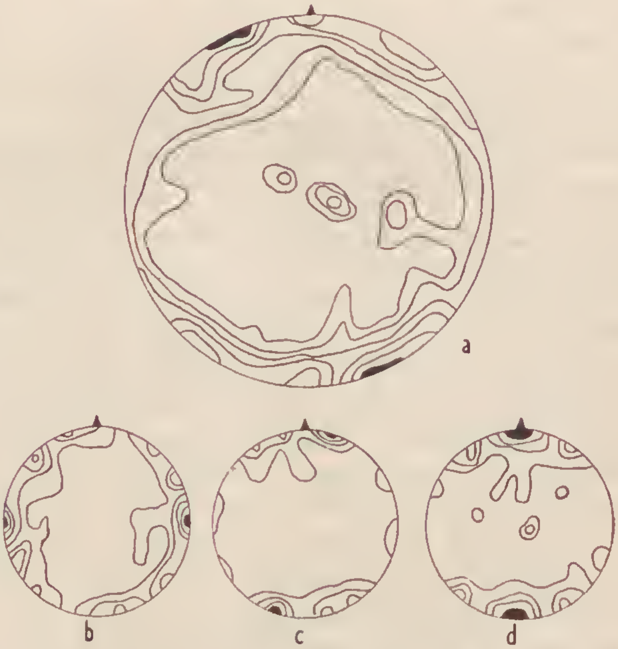

FIG. 9—Fault patterns in the Kiewa Area.

a. Poles to 940 faults in the area. Contours 6-5-4-3-2-1%.
b. Poles to 208 faults, sub area 1A of Fig. 6. Contours 5-4-3-2-1%.
c. Poles to 275 faults, sub areas 2A and 2B. Contours 4-3-2-1%.
d. Poles to 350 faults, sub areas 4A, 4B, 4C. Contours 4-3-2-1%.

of the quartz diorite. Lacking more positive evidence the possible contact of the two intrusive masses must be regarded as little more than speculation.

Several very strong faults with some interesting features, but lacking the significance of those described, have been studied. The Sassafrass Creek Fault is a high angle thrust of restricted exent, marked by a belt of brecciated mylonite 400 ft thick. Bores along the fault recorded alluvials at depths of up to 110 ft, suggesting that these were involved in the latest movements. Where the alluvials are exposed near the fault, the maximum thickness is 20 ft. The fault strikes E.-W., with dip 65°N. The best exposure of this fault is in Howman's Gap, where movement was a mixinum of 200 ft. Along the strike from here, both to the E. and W., displacement appears to have diminished rapidly.

The Tail Race Fault, natural exposures of which are infrequent, was first recorded in the No. 4 Tail Race Tunnel between chainage 4,450 and 4,748 ft. The material of the crush zone is a fault conglomerate. Strike is N.-easterly, dip vertical. The fault conglomerate has been recognized only sporadically at the surface.

The trend of the major faults varies, but a N.-easterly trend is dominant, with E.-W., and S.E. less important. This applies more or less for the area as a whole (Fig. 9). It can be seen that the great majority of the faults are steeply dipping. The field work suggested some marked variations in the fault pattern from place to place throughout the area. To investigate this apparent variation, the areas in which most detailed work was done were divided into sub areas, each dominated by a major fault. Patterns were analysed for each of three sub areas: the results of the analyses are shown in Fig. 9 b-d, and in Table 12.

TABLE 12

Variation in Fault Patterns, Kiewa

Sub area	Main Trend	Subsidiary Trends		
4	90°	N.52°E.		S.55°E.
2	S.77°E.	N.56°E.		N.75°E.
1	N.-S.	N.48°E.	N.74°E.	S.26°E.

Examination of each of the sub areas shows some interesting relationships. E.g. the No. 4 area is dominated by the Tawonga Fault; the fault system is regular, with one subsidiary set of faults more or less parallel to the Tawonga Fault. An equally important aspect is the symmetry, the main set, striking E.-W., making angles of 38° and 35° with the subsidiary sets.

In the No. 1 area, a comparable, but less striking symmetry is found. Here the major set, striking N.-S., makes angles of 26° with two of the subsidiary sets, but 48° with the third. Sassafrass Creek Fault, the most important structure in this area, does not appear significantly to have influenced the overall fault pattern. The Turnback Creek Fault has a set of associated minor faults, the pattern of which has the same relationship to the main fault as that observed for the Spion Kopje Fault system.

In the No. 2 area, the main set of faults is parallel to the Spion Kopje Fault, and although there is a certain symmetry with the minor sets, this is not as impressive as in the other cases examined.

The relationship between major faults and adjacent minor, possibly syngenetic, faults, was studied in some detail at the No. 1 Underground Power Station. A total of 155 minor faults was mapped in an area of 20,000 sq. ft. A single strong maximum was found, with strike N.-S., dip 90°. Very weak sets with steep dips, with strikes N.32°E. and N.40°W., and a set of flat faults were recorded. The main structure, the Power Station Fault, has strike N.80°W. and variable dip (more or less vertical). Minor structures parallel to the main fault are rare, and most intersected the main fault at angles of 20°, 32°, and 42°. There is here, thus, no clear relationship unless, as shearing proceeded on the main structure, rotation of one set of minor faults took place, as a second set was developed.

Overall, it is clear that on a broad scale, the pattern of minor faults can be related to the major fault in only isolated cases, and in most, no relationship can be proved.

JOINTING

Jointing was studied in terms of the patterns in individual rock types, variation in patterns, independently of rock type, and the regional patterns. Three genetic classes of joints were recognized: contraction joints, tectonic joints, and erosion joints. The erosion joints, or sheeting, due to elastic recovery of the rock with erosional unloading, appeared in some cases to have developed on tectonic joints, and complete separation was not always possible. Flat tectonic joints were observed in tunnels at depths of 1700 ft, where sheeting would not be expected to have occurred.

Columnar jointing is highly developed in all of the basalts. The columns vary in diameter from 3 inches to over 2 ft, and with one exception, the columns are more or less vertical. At Ruined Castle, a wide variety of attitudes was recorded, with horizontal columns at the W. end, and elsewhere plunging at 60° in various directions. The deviations from vertical were always found in association with faults. Primary joints were not recognized in any other rocks in the area, though almost certainly, some are present.

Sheeting was observed both in natural outcrops and in excavations; it was invariably accompanied by seams of decomposed rock. The sheeting was always subparallel to, and less steep than, the natural surface. Where sheeting outcropped on steep slopes, it tended to control the stability with respect to sliding of such slopes. This was seen at Clover Dam. Sheeting has developed independently of rock type, cutting across geological boundaries with little or no deflection; similarly, the sheeting was observed to cut across faults and tectonic joints without deflection. The seams of weathered rock found on the sheeting increased in thickness rapidly with the excavation of the overlying rock: at Clover Dam, one such seam increased in thickness from 2·45 ft to 2·96 ft within three months.

In the more arenaceous of the Upper Ordovician sediments, two equally prominent sets of joints have been developed. One set, normal to the axial planes of the folds, appear to be *ac* joints, and are concentrated near the fold axes. Less common, but still important are *h0l* joints, with strike parallel to the fold axes, but cutting the axial planes at angles of from 30° to 90°. Least well developed are *hkl* joints. These are generally steeply dipping. The pattern is shown on Fig. 10a. To what extent these joints were due to folding, or to later deformations, is uncertain, since the pattern corresponds closely with that found in much younger rocks in the area.

Too few joints were mapped in the schists for statistical treatment to be attempted. Both *ac* and *h0l* joints were recognized, the latter tending to be more frequent than the former. Dominating both were *hkl* joints, the result of shearing. These joints were invariably strongly slickensided.

Jointing is exceptionally strong in the permeation gneiss. At most exposures,

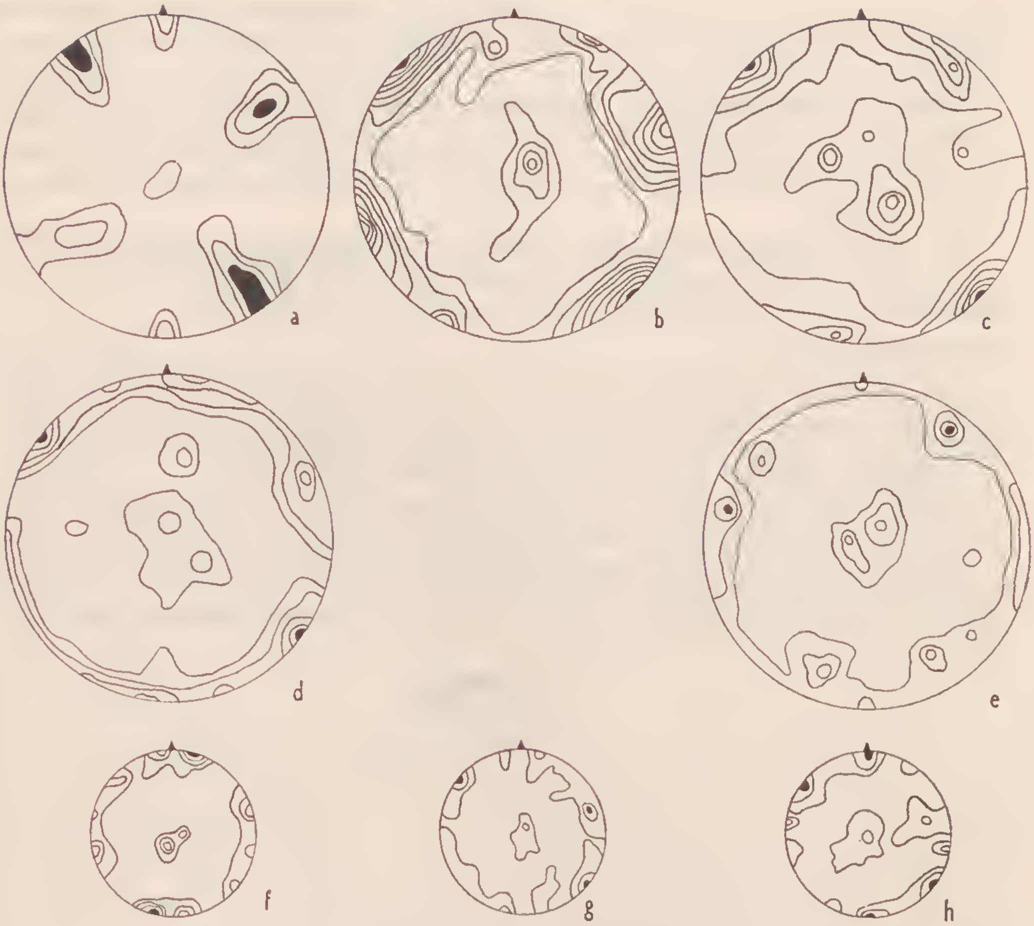

FIG. 10—Joint Patterns in the Kiewa Area.

a. Poles to 75 joints, Upper Ordovician Sediments. Contours 6-3-1%.
b. Poles to 1513 joints in permeation gneiss. Contours 8-7-6-5-4-3-2-1%.
c. Poles to 1262 joints, Granodiorite. Contours 9-5-4-3-2-1%.
d. Poles to 2871 joints in the area. Contours 5-4-3-2-1%.
e. Poles to 106 joints, gneissic granodiorite. Contours 4-3-2-1%.
f. Poles to joints in sub area 1A of Fig. 6. Contours 5-4-2-1%.
g. Poles to joints in sub areas 2A and 2B. Contours 5-3-1%.
h. Poles to joints in sub area 4A, 4B, 4C. Contours 5-3-1%.

three sets occur: one set has N.-easterly strike with vertical dip, the second N.-westerly strike with dip 70° to 80° SW., while the third set is flat. This system is clearly shown for the whole of the gneiss in Fig. 10b; the figure emphasizes the dominance of the first set.

Two main sets of joints intersecting at 60° are dominant in the granodiorites (Fig. 10c), while a third set, striking WNW., and with vertical dip, is less strong. One of the main sets coincides with the strongest set of the permeation gneiss. Again, flat joints are important. There is evidence of several ages of jointing in the granodiorites (Pl. XLI, fig. 1). At Fall's Cr., lamprophyre dykes have been intruded along joints, while later joints cut both the lamprophyre and the granodiorite.

Jointing of the lamprophyres appeared generally to be the result of shearing. Usually, two sets, intersecting at 60° were present. Exposures of the quartz diorite were too poor for detailed study of jointing. One set, N.70°E. is strong, and these may have been primary, since they are parallel to the flow structure in the upper levels of the mass.

The regional pattern of jointing for the area as a whole requires little comment at this stage. NE. striking joints are dominant (Fig. 10d). Marked variations occur from place to place; these variations are discussed later in the paper.

DYKE INTRUSION

The swarms of intermediate to basic lamprophyres, basalt, dolerite and phonolite dykes which occur throughout the area are only part of much larger swarms distributed throughout E. Victoria. One of the most notable features of the Kiewa swarm is the persistence of the almost E.-W. strike (Fig. 11a).

The thickness of the dykes is remarkably constant, 76% of those mapped having thickness less than 10 ft, while 50% have thickness between 1 and 5 ft. Only one dyke was mapped with thickness greater than 50 ft. Dip is usually vertical, and only rarely were dykes recorded with dip less than 60°. In the field, the constant association of dykes with the crush zones of faults was notable, the dykes occurring

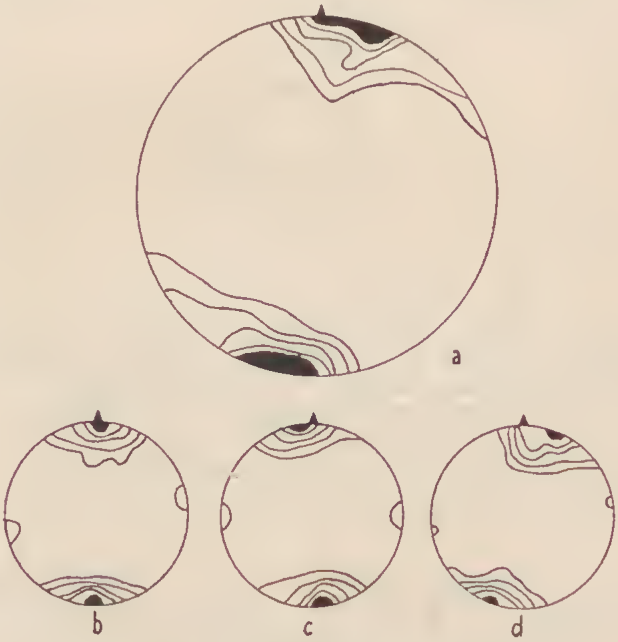

FIG. 11—Dyke Swarm at Kiewa.

a. Poles to 863 dykes. Contours 8-4-3-2-1%.
b. Poles to dykes, sub area 1A, Fig. 6. Contours 5-4-3-2-1%.
c. Poles to dykes, sub areas 2A and 2B. Contours 5-4-3-2-1%.
d. Poles to dykes, sub areas 4A, 4B, 4C. Contours 5-4-3-2-1%.

in groups of 3 or 4 on the walls of the crush zones. There are both local and regional departures from the statistical trend. E.g. there is a westerly swing of 20° in sub area 4, comparable to that noted for the fold axes; the areal trend also differs markedly from that for E. Victoria as a whole. At Kiewa, both field and statistical evidence support that faults controlled dyke intrusion. Elsewhere in E. Victoria, other controls operated, as at Woods Point, where the dykes were intruded along the axial planes of the folds.

Field and Tectonic Relationships of the Structural Elements

Theoretical aspects of folding, faulting, jointing and dyke intrusion have been summarized by Anderson (1954), Billings (1954), McKinstry (1953) and Moody and Hill (1956). These workers have concluded that planes of failure in rocks make angles of less than 45° with the direction of maximum compressive stress, with an average value of this angle 30°. Experimental studies by Doubree (1879), Bucher (1920), Mead (1920), Riedel (1929) and Cloos (1932), in conjunction with theoretical analyses, have formed the basis for the interpretation of structural mapping. The recent study of structure in the Beartooth Mountains, U.S.A., by Spencer (1959), which was based on experimental results, is of particular importance in the present work because of the similarity of that area to the Kiewa area.

Spencer found that dyke intrusion had occurred along pre-existing fractures. A comparison of fracture patterns and folds in granite gneiss showed no consistent relationship between the two, although in some instances, the joints made angles of 30° with the fold axes; these joints were interpreted as conjugate shears related to the folding. Some joints were parallel to the fold axes, and some normal to the axes. These were regarded as tension joints due to folding. The multiplicity of patterns of jointing and faulting throughout the area was regarded by Spencer as due to later deformation of small blocks which had uniform and simple patterns when first deformed. Superposition of patterns gave an overall simple pattern, which suggested that rotation had not taken place; if there had been rotation, a large number of trends would have been expected. In determining the mechanics of deformation, Spencer adopted the Mead model, and found close agreement.

In the study of the relationships at Kiewa, the first phase of the work was the study of relationships in small areas. Table 13 shows the regional trends of faults, dykes and joints throughout the area. The data presented on the table does not emphasize any obvious relationship between the trends, although there is a tendency for a concentration in the 90°-110° range. This examination on a regional scale does not take into account such factors as the influence of major faults and of varying rock type, both of which have been seen to be significant.

The control of such factors can be considered, and their influence eliminated, by the careful selection of small sub areas for study. Those selected were 2A, 4A, 4B, and 4C of Fig. 6, with a more general study of areas 1, 2, and 4. The results of the analyses are shown in Fig. 12, and in Tables 14, 15, and 16.

Table 13

Regional Trends of Joints, Dykes and Faults

Structure	Main Trend	Subordinate Trends	
Faults	65°	90°	120°
Joints	40°	110°	155°
Dykes	100°		

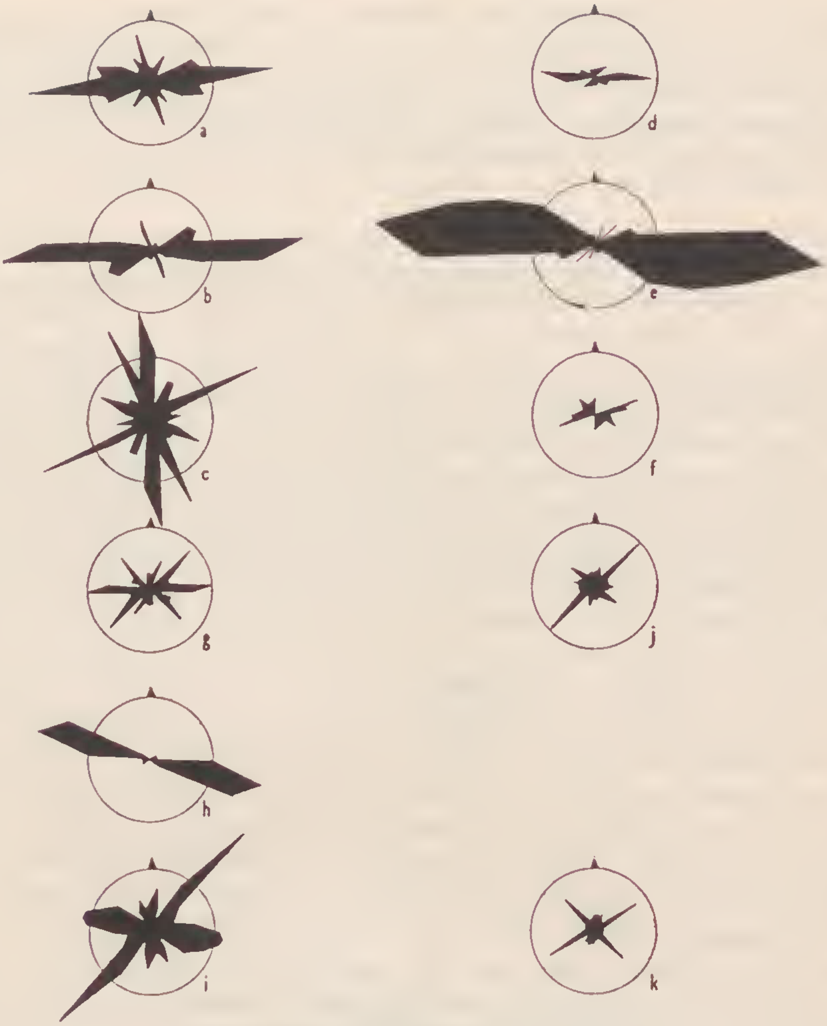

Fig. 12—Structural Trends in the Kiewa Area.
Radius of circle represents 10 structures.

a. Faults in sub area 2A of Fig. 6.
b. Dykes in sub area 2A.
c. Joints in sub area 2A.
d. Faults in sub area 4A.
e. Dykes in sub area 4A.
f. Joints in sub area 4A.
g. Faults in sub area 4B.
h. Dykes in sub area 4B.
i. Joints in sub area 4B.
j. Faults in sub area 4C.
k. Joints in sub area 4C.

TABLE 14

Trends of Structures in Three Sub Areas

Sub area	Structure	Main Trend	Subordinate Trends	
4	Faults	90°	52°	135°
	Joints	90°	38°	
	Dykes	110°		
2	Faults	103°	75°	
	Joints	162°	38°	
	Dykes	80°		
1	Faults	48°	74°	118°
	Joints	105°	165°	
	Dykes	90°		

The No. 4 sub area shows the symmetry previously described. The main joint set is parallel to the main fault set, while one subordinate joint set is sub-parallel to a subordinate set of faults. The dykes are sub-parallel to the main sets of faults and joints. In the No. 2 sub area, there is no clear relationship, although the joint sets are more or less symmetrically disposed about the main fault trend, making angles of 56° and 65° with this trend. The lack of a statistical relationship between faults and dykes in this sub area was contrary to the conclusions reached in the field where the dykes and faults were intimately associated. In No. 1 sub area, again, no clear relationship was found: this led to the more detailed analysis which follows.

In the No. 4 sub area, three small sections, all in permeation gneiss, were selected: 4A, on the spur joining Mt Beauty and Big Hill; 4B, the No. 4 Underground Power Station area; 4C, near Mt Beauty Village, adjoining the Tawonga Fault. Some of the structures used in the general analysis of the No. 4 sub area were excluded from the detailed study because of the selection of these restricted sections. The results are shown on Table 15. Each of the small areas shows a close relationship between the trends of the several structural elements, although the dominant trends vary from place to place. In the 4A area, there is a single fault trend at 90°. Although the main joint set bears little relation to this, two of the subordinate joint sets do, one being parallel to the fault set, the other normal to it. Parallelism of the faults and dykes is emphasized. In the 4B area, the relationship between the patterns is even more obvious.

TABLE 15

Trends of Structures in No. 4 Sub Area

Area	Structure	Main Trends	Subordinate Trends		
4A	Faults	90°			
	Joints	70°	90°	130°	0°
	Dykes	90°			
4B	Faults	45° 95°	135°	25°	0°
	Joints	45°	100°	150°	0°
	Dykes	105°			
4C	Faults	45°	15°	90°	135°
	Joints	50° 135°		0°	45°
	Dykes	Data inadequate for analysis			

In the No. 2 sub area, two small sections were selected: 2A, on the Junction Spur, between Bogong and Howman Gap, in granodiorite; and 2B, on Spion Kopje, in permeation gneiss. The results are shown in Table 16.

TABLE 16

Trends of Structures in No. 2 Sub Area

Area	Structure	Main Trends	Subordinate Trends
2A	Faults	85°	30° 60° 105° 145° 160°
	Joints	175° 150° 60°	115° 95° 25°
	Dykes	95°	160°
2B	Faults	45°	20° 105° 145° 175°
	Joints	5° 90° 135°	30° 170°
	Dykes	Data inadequate for analysis	

Here, in spite of the multiplicity of patterns, the spatial relationships of the structures are clear.

The localized influence of major faults on the adjacent minor faults and joint patterns is seen, in these detailed studies, to be considerable, in contrast to other sectors previously described, where the influence of the major faults appeared to be insignificant. It is clear that the age relationships may have a considerable bearing on the spatial and tectonic relationships of the fracture structures; this aspect is considered below.

The relationship between joints and folds in the sedimentary and metamorphic rocks is not always clearly defined. The joint pattern of the sediments and schists is comparable to that for the whole area, regardless of lithology, and the question arises whether or not these joints may be of post folding age. It is more likely that joints were developed as a result of shear and tensile stresses during folding, the joints so formed receiving an emphasis during later deformations. In the permeation gneiss, statistical analyses show no relationship between the folding and jointing. In selected areas, however, the same relationship as that seen in the sediments, has been observed. On the No. 4 Head Race Tunnel line, two sets of joints make angles of 20° with the axial planes of the folds in the gneiss, while a third set is more or less normal to the axial planes.

In the gneissic granodiorite, one set of joints is parallel to the foliation, while a second set is almost normal to the foliation. The joint pattern of the gneissic granodiorite is unlike any other in the area, and it is probable that the shearing which produced the foliation resulted in the development of the joints.

From the detailed study of fracture patterns in the area, it is possible to develop ideas relating to the way in which the Kiewa area fits the general tectonic pattern of the East Australian Mobile Belt, as well as determining the detailed tectonic development of this small sector of the Belt. Hills (1947, 1955a, 1955b, 1956) has shown the importance of N.-easterly and S.-easterly structural trends in SE. Australia. The major trends at Kiewa, 60° and 160° fit this pattern while the other trends here, 45° and 90° are (approximate) bisectrices.

Assuming that the major diastrophisms of the Lower Palaeozoic were effective at Kiewa, and it has been shown that there is strong evidence for this assumption, an attempt has been made to relate structural trends in the area to each of these deformations. The orientation of the principal compressive stress for each orogeny has been assumed from the orientation of fold axes in sediments affected by the orogeny. Thus, for the Benambran Orogeny, the fold axes of the Upper Ordovician sediments, schists and gneisses strike N.15°W.; for the Bowning Orogeny, the Lower-Middle Silurian beds at Wombat Cr. have folds striking N.35°W.; the fold axes of the Middle Devonian beds at Buchan, folded during the Tabberabberan Orogeny (Teichert and Talent 1958) strike almost due N.

If the Spencer-Mead patterns are taken as a basis, and if it is assumed that each orogeny developed its own characteristic fracture pattern, the pattern for Kiewa would be as shown on Table 17.

TABLE 17

Theoretical Fracture Pattern

Tectonic Episode	Orientation of principal compressive stress	Fold Axes	Shears	Tension Fractures	Thrusts
Benambran	N.75°E.	N.15°W.	N.45°E. S.75°E.	N.75°E. S.15°E.	S.15°E.
Bowning	N.55°E.	S.35°E.	N.25°E. N.85°E.	N.55°E. S.35°E.	S.35°E.
Tabberabberan	W.-E.	N.-S.	N.60°E. S.60°E.	N.-S. E.-W.*	N.-S.
Kosciuskoan	S.45°E.	N.45°E.	S.15°E. S.75°E.	S.45°E. N.45°E.	N.45°E.

* Trend of basic lamprophyre dykes of Tabberabberan age.

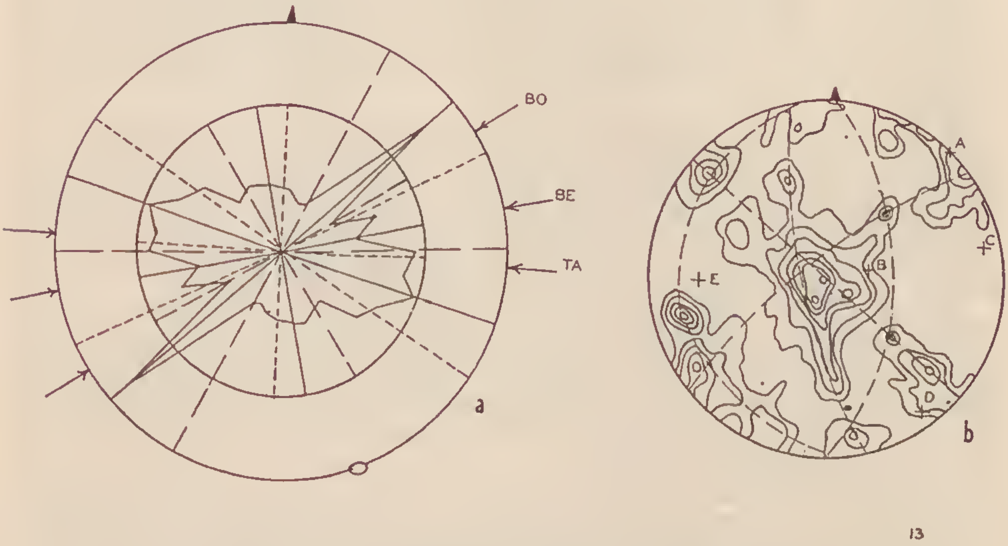

FIG. 13—Regional Structural Patterns.

a. Pattern of 3206 joints and faults, with theoretical shears (drawn to outer circle) and theoretical tension fractures (drawn to inner circle). The solid lines are Benambran fractures, the dashed lines Bowning, and the dotted lines Tabberabberan.

b. 1256 β points for faults and joints. Contours 3-2½-2-1½-1-½-¼% per ½% unit area.

Superposition of the actual fracture pattern on this assumed theoretical fracture pattern (Fig. 13) shows remarkable agreement between the two. This explanation of the fracture pattern at Kiewa depends on the validity of the basic assumptions that the three Palaeozoic orogenies were effective, that the pre-existing systems were modified only slightly or not at all by later deformations, and that each orogeny produced its own system of fractures. It should be noted that all of the fractures which could be produced by the Tertiary Kosciusko deformation, could also have been developed by earlier deformations.

Examing more closely the basic assumptions, there seems little doubt that the stresses associated with the Palaeozoic orogenies were effective at Kiewa, when strong direct evidence is available from all of the surrounding area. The assumptions that each stress application produced a new. independent fracture system, and that the earlier systems were little affected, are more difficult to consider, especially when there is clear evidence of rotation of at least one block. The former is reasonable, and finds support in the results of experimental deformation.

The validity of the assumptions, and to some degree, of the theory itself, can be tested by comparing the fracture patterns of the rocks affected. Thus the older sediments, schist and permeation gneiss should show the imprint of all the deformations; the grandodiorite of the Bowning, the Tabberabberan and Koscuisko; the quartz diorite, the Tabberabberan and Koscuisko; and the basalts, the Kosciusko only. Such testing is not simple since, as Table 17 shows, some trends are common to more than one deformation.

In the simplest cases, the basalts, only faults can be studied, since any tectonic joints are obscured by the primary jointing. All of the faults recorded occupy precisely, or in isolated cases, approximately, one of the four trends possible for the Kosciusko episode: N.45°E., E.75°E., E.45°E., and S.15°E. In the quartz diorite, too few measurements could be made for certain investigation, but the main trends recorded were N.-S., E.-W., N.45°E., N.60°E., S.60°E., and S.15°E. When the older rocks are examined, the multiplicity of patterns becomes evident, but there is a definite emphasis on the pattern which would have resulted from the Benambran Orogeny.

The two dimensional analysis of the fractures just described takes no account of the numerous flat lying structures mapped. For the analysis to be complete, such flat structures must be considered, since neglect of these could result in the failure to recognize some possibly important aspects of the tectonics. A three dimensional analysis would be expected to lead not only to the geographical orientation of the stresses, but also the inclination from the horizontal of these stresses.

For this analysis, conjugate pairs of fractures were plotted at projections on the Schmidt equal area net. The line of intersection of each pair of planes is then represented as a point on the projection. On completion of the plotting, the point diagram resulting, was contoured in the usual way. Fig. 13b was prepared in this way for 1256 points; plotting of a greater number of points was not practicable. Counting was with a ½% counter.

The maxima of the diagram are seen to lie on five girdles, the poles of which represent the orientation of principal compressive stresses, as shown on Table 18.

The trend A is to be regarded as the orientation of the principal compressive stress of the Bowning Orogeny; B and C, the Benambran; D, the Kosciuscoan; and E, the Tabberabberan. As would be expected, the stresses are, with one exception, sub-tangential. The development of the near vertical stress B was probably associated with the late stages of Benambran activity.

TABLE 18

Pole	Trend	Plunge
A	N.42°E.	5°
B	N.72°E.	70°
C	N.77°E.	10°
D	S.38°E.	16°
E	E.-W.	25°

This analysis depends on the relationship between the principal compressive stress and the strain axes, based on theory discussed at length by Jaegar (1956) and Anderson (1951). The girdles containing the maxima lie in the plane defined by the least and intermediate principal stresses.

RESUME OF STRUCTURE AND THE RELATIONSHIP BETWEEN STRUCTURE AND IGNEOUS ACTIVITY

The general picture that has emerged from the study of folding at Kiewa is of a major anticline, the axis of which has a gentle northerly plunge, with local plunge to the S. The W. limb of this fold has been sheared through on the West Kiewa Thrust. Minor complexities occur, but overall the fold is a relatively simple structure. On a broader scale, it is possible to conceive of this structure as being a minor fold associated with the Geanticline, described by David, which developed in the East Australian Mobile Belt during the Benambran Orogeny.

Statistical geometry of the folds indicates only one period of folding, the Benambran, although the area has been subjected to at least four deformations. Erosion had proceeded to an advanced stage by the late Silurian, so that the rocks at present exposed, were at no great depth in the crust during the post Benambran deformations. The condition of the rocks under such conditions would be brittle rather than plastic, and any strain would be represented by fracture rather than flexure.

The fractures are the most important structural elements in the area. Examination of detailed geological maps of SE. Australia suggests that the Eastern Highland belt is somewhat unique (cf. Hills 1956) in the intensity of fracturing. This leads to the consideration of the Eastern Highlands as a great crush zone. As suggested by Hills (1956) and confirmed for the Kiewa area at least by the present work. many of the faults are high angle thrusts. Several important wrench faults have been recorded, but normal faults are rare. Four trends are outstanding: N.-easterly, easterly, S.-easterly, and N.-S. These trends are important throughout the Eastern Highlands, and conform to the network of Vening Meinesz (1947).

The N.-easterly trend is particularly significant since faults with this trend tend to form the W. boundary of the Highlands. Although faults with this trend are among the oldest, Tertiary faulting, including renewed movement on older structures, follows this direction. The late uplift of the Highlands is indubitably the result of these movements. The late movements are expressed by a gentle fault controlled warping, giving rise to a broad, faulted anticlinal structure, with a N.-easterly trending axis. During the Benambran Orogeny, the only certain manifestation of igneous activity was migmatization, accompanied by granatic pegmatites. The relationship between folding, metamorphism and migmatization was close, and all three are to be regarded as occurring contemporaneously. The migmatite is completely concordant with sedimentary structures present in the permeation gneiss. At Kiewa certainly, and probably in other areas which were examined cursorily in the present work (e.g. Dartmouth, in the Mitta Mitta valley), the migmatites are restricted to the cores of major anticlines.

The migmatization possibly slightly pre-dated the West Kiewa Thrust, which forms the W. boundary of the migmatite at Kiewa. The thrust, however, exerted a major control on later intrusions. The granodiorites probably represent the stage of late tectonic intrusion of the Bowning Orogeny, extending into the post tectonic stage. The two main masses, the Niggerheads and the East Kiewa, as well as the Pretty Valley gneissic granodiorite, crudely elliptical in shape, have long axes parallel to the structural grain of the country, and, in a sense, are concordant, although when closely examined, are discordant, at least locally. The major axes of these intrusions are coincident with one of the tension (relaxation) directions of the Bowning Orogeny, and it is likely that both the intrusion and the shape of the intrusive masses was controlled by this factor.

The proximity to, and the elongation along, the West Kiewa Thrust of both the Niggerheads granodiorite and the gneissic granodiorite of the Cobungra R., suggest that the Thrust may have exerted some control over intrusion and, in fact, may have provided ready access for the magma. On the other hand, if this were the case, more intense intrusion of the crush zone of the thrust itself would be expected.

The intrusion of the quartz diorite was almost certainly controlled by post tectonic relaxation associated with the Tabberabberan Orogeny, while the intrusion of the lamprophyre dykes occurred more or less at the same time along tension cracks and 'openings' in crush zones. The almost exclusive E.-W. orientation of the dykes supports this view.

The extrusion of the basalts was associated with the development of tension in the early stages of the Kosciuscoan movements. The main centres of eruption at Kiewa fall on a line coincident with a tension trend for this deformation.

Three more general relationships between igneous activity and structure may be considered. The first of these is the influence of the West Kiewa Thrust on the distribution of intrusive masses. It can be seen in Fig. 1 that the area immediately E. of the Thrust is marked by a large number of small intrusive masses; such masses are absent W. of the Thrust. One of the more obvious conclusions is that the movement on the Thrust, with upthrow to the E., and therefore accelerated denudation, has led to the exposure of these masses. An alternative is that the mylonite zones of the Thrust formed a barrier against the magma, but the reverse would in fact be expected, i.e. that the crush zone would facilitate magma migration.

The former hypothesis is the more attractive. Movement on the Thrust is unknown, but almost certainly it would have been of the order of tens of thousands of feet. In addition, movement occurred during several periods, and for the hypothesis to be tenable, one such movement, post dating the Tabberabberan intrusion of the quartz diorite, would be necessary. No definite evidence for this is available. The evidence of the near roof schlieren and other flow phenomena at Big Hill suggests that the exposure is close to the original roof. It is possible that other masses occur W. of the Thrust, but are not yet exposed. The evidence for this is slender, and reference can be made only to the general low grade metamorphism shown by some of the Upper Ordovician sediments W. of the Thrust.

The second general relationship to be considered is that of the intrusive masses to structure. Thom (1955) has discussed wedge uplifts, taking as an example, the Beartooth Mountains, U.S.A. These wedge uplifts are essentially coincident in size and outline with granitic batholiths, which have 'headed' as they approached the surface thus giving, on cooling, massifs with the shape of downward pointing wedges. Although such structures were considered, there is no evidence for their development at Kiewa. It is important to note, however, that most of the submeridional boundaries of the intrusive masses are faulted, with the faults almost invariably high angle thrusts. Besides these, there are a number of others which together impose on the area a type of imbricate structure. That the igneous boundaries are so frequently faulted is due less to chance than to the structural weakness of the normal contacts, and to the original orientation of the contacts in a direction parallel to shear directions of post intrusive deformations.

Finally, the structural relationships of the dyke swarms may be considered. It has been shown that the dykes at Kiewa have a consistent E.-W. trend, and this has been related to tensile relaxation of the Tabberabberan orogeny. In considering the structural relations of the swarm as a whole it must be remembered that dykes of varying petrographic type, and of varying age are represented. Additionally, rocks with markedly different structure are hosts to the dykes. In the Palaeozoic sedimentary belts, the dykes have trend parallel to the fold axes (Woods Point, Ovens Valley, Bendigo). The dykes of South Gippsland which intrude Jurassic sediments are generally normal to the monoclinal axes.

In North East Benambra, the dykes are intrusive into igneous and metamorphic rocks, the structure of which is virtually unknown. These dykes have a trend normal to those at Kiewa, with the exception of one group which strikes N.-easterly, parallel to an important shear direction in this region. Dyke intrusion appears to have been controlled by both host rock structure, and stress conditions during intrusion.

STRUCTURAL CONTROL OF TOPOGRAPHY IN THE KIEWA AREA

Within the Kiewa area, the summits of all the more important peaks are at elevations of more than 6,000 ft, some hundreds of feet above the general level of the Bogong High Plains. The gently undulating topography of the High Plains, in strong contrast to the surrounding, deeply dissected areas, is found not only on the High Plains proper, but also on the divides between the various branches of the Kiewa R., and between these and the Mitta Mitta and Ovens R. This suggests a former continuity of this mature, gentle terrain. One of the more important features of the mountains is the accordance of summit levels, as shown on Table 19.

TABLE 19

Peak Accordance: Kiewa

Mountain	Elevation (ft)	Mountain	Elevation (ft)
Fainter North	6120	Nelse North	6273
Fainter South	6249	Spion Kopje	6117
Niggerheads	6150	Arthur	5575
Loch	6244	Bogong Central	6527
Hotham	6193	Little Bogong	5558
Jim	6008	Feathertop	6398
Cope	6116	McKay	6137
Nelse	6257	Little Spion Kopje	5278
Bundarrah	5745	Bogong	6601

Note: Elevations are those of detailed topographic maps used and are based on S.E.C. false datum 92 ft above M.S.L.

A series of broad, mature, alluviated valleys, ranging in elevation from 5,300 ft (Rocky Valley) to 5,800 ft (Big R.), occur on the Bogong High Plains, and from these, gentle divides rise to elevation 5,800 ft in the S. and 6,300 ft. in the N.

To the NW. of the Tawonga Fault, there is a marked change in the topography. The average elevation of the divides is 4,000 ft, with the terrain at the stage of early maturity. The uplift to the SE. of the Tawonga Fault has resulted in rejuvenation of drainage of the uplifted block, and the Bogong High Plains are a remnant, as yet unaffected by headward erosion, of the pre-uplift terrain. If the High Plains are thus regarded, a new approach can be made in assessing the factors responsible for the maturity of the high plains valleys.

Kenny (1937) explained the valleys by postulating blockage by the Older Basalts, with lake formation. This is unacceptable since there is no doubt that the present stream system post dates the Older Basalts. Crohn (1949) postulated reduction in grade of the streams due to a S.-easterly tilt which accompanied the uplift on the Tawonga Fault, and cited as evidence the 'lack' of alluviated valleys on the SE. margins of the plains. Such valleys, however, do occur on the S.-easterly margin, notably Jack Cr. Carr and Costin (1955) attempted to explain Rocky Valley by the blockage of the stream with Pleistocene moraine at Langford's Gap. This has been shown (Beavis 1959) not to be tenable since no moraine occurs on the Bogong High Plains. It is considered that the alluviated valleys are merely remnants of the pre-uplift valleys, evidence of which can be traced downstream from the high plains in the valley in valley structures.

Fig. 14—Tertiary Warping in Eastern Victoria.

If the mountain and high plains areas of E. Victoria are considered on a broader scale, it can be seen that there is a basic structural control of the topography. On the broadest scale, warping on a NE.-SW. axis is apparent. If the elevations of all the mountains are plotted (Fig. 14) and contours constructed, the distinct warp can be clearly seen with the axis passing through Cobbler and Mt Bogong to Mt Kosciusco in N.S.W.

The E. margin of the warp is broken by the Tawonga Fault, and possibly by other young faults parallel to this. The warping and faulting were contemporaneous and, in fact, the warping is to be regarded as an expression of fault movement. Thus,

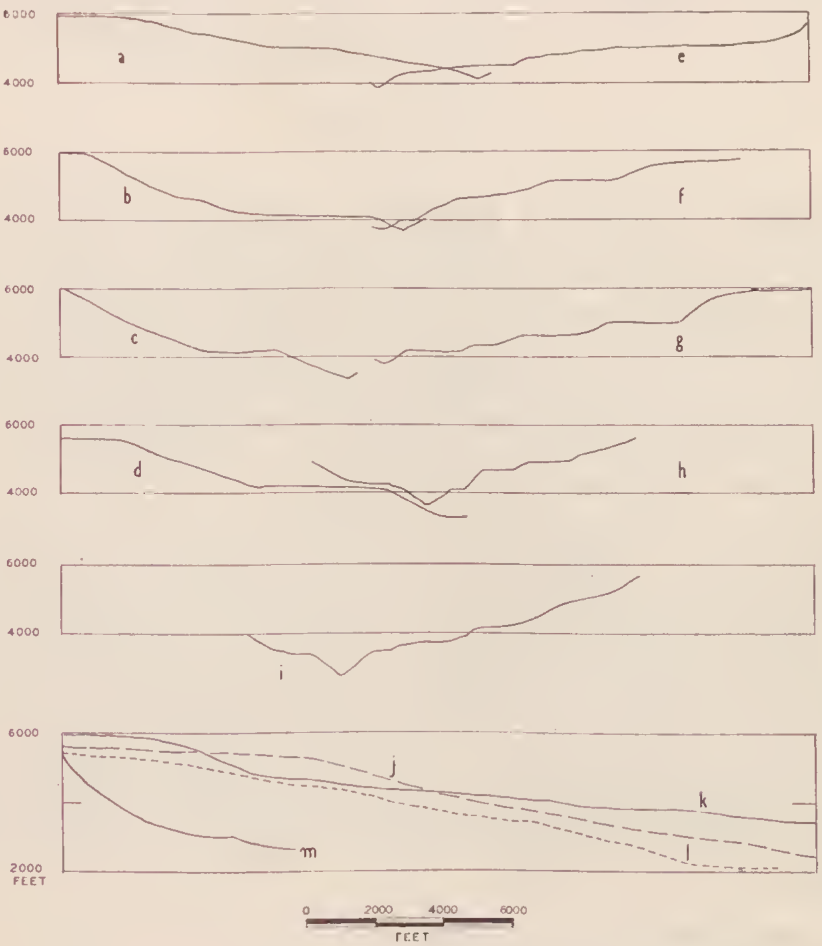

FIG.15—Valley Cross Sections and Stream Gradients, Kiewa.

a.-h. Cross sections of Big R. valley.
i. Cross section, East Kiewa R. valley.
j. Stream gradient, Pretty Valley.
k. Stream gradient, Big R.
l. Stream gradient, Rocky Valley.
m. Stream gradient, Spion Kopje Cr.

on the W. margin of the warp in the Kiewa area, we have going from E. to W., the Sassafrass Creek Fault and minor parallel faults, the Tawonga Fault, the Bright Gap Fault, and the Running Creek Fault, all with upthrow to the SE. On the E. side, little work has been done, but it is probable that faults with upthrow to the NW. occur, comparable to the Livingstone Creek Fault described by Crohn (1949).

Continuation of the axis of warping to the SW. shows that many of the elevated plateaux such as the Dargo High Plains and the Baw Baws fall on the axis. Thus the mountain belt of E. Victoria may be ascribed to this Tertiary fault-warping. It follows that the stream development would be modified by the warping and, while on a local scale, faulting alone seems to have acted as control, on a regional scale the warping has been the dominant factor. This concept agrees in part with Crohn's idea of tilting to the SE., but with the warp axis passing through the Bogong High Plains, tilting to the NW., not recognized by Crohn, also occurred.

THE DEVELOPMENT OF THE STREAM SYSTEM

MITTA MITTA RIVER—

The main tributaries of the Mitta Mitta R. which have their sources on the Bogong High Plains are Big R., Middle Cr., and the Cobungra and Bundarrah R. Big R. has its source on the W. slopes of Mt Nelse and the N. slopes of Spion Kopje; the headwaters are mature, with alluviated valleys, and stream gradient 1 : 250. Initially, the stream flows westerly, but near the knick point, separated from Spion Kopje Cr. by a low saddle, elevation 5,750 ft, the stream turns sharply to the N. The elevation of the knick point is 5,800 ft. The northerly trend is maintained to elevation 4,150 ft, where the stream turns sharply W., with a low saddle, 4,600 ft separating the Big R. from Bogong Cr. It is obvious that both of the low saddles mentioned were formerly occupied by streams and that, Big R. has captured the headwaters of both Spion Kopje and Bogong Cr.

The valley of Big R. is markedly asymmetric (Fig. 15) a feature typical of all the valleys in the area. The slope of the S. wall averages 1 : 3·5, while that of the N. wall averages 1 : 5·5. There is a sharp flattening of the spurs at elevations 4,200-4,000 ft, 5,000 ft, and 5,800 ft. The floor of the valley is locally strongly alluviated, long narrow alluvial flats occurring on alternating sides of the streams downstream from elevation 4,150 ft (in the stream bed). Much of this alluvium has had its origin in landslip debris; large landslips are a feature of the valley walls. In one section between the source and the foot of T Spur, development of the stream on the crush zones of faults has been proved, and it is a reasonable assumption that the rectangular pattern of the streams throughout this catchment is due to the same control. Locally, as near the junction of Cairn Cr. with Big R., the main stream has left, for no apparent reason, a strong crush zone. Whether or not activity on faults so late in the history of the area has been responsible for this is a matter for conjecture.

KIEWA RIVER—

The two main branches of the Kiewa R.—the West Kiewa and the East Kiewa—have their junction immediately downstream from Mt Beauty village. The junction of the two main branches of the East Kiewa R.—Pretty Valley and Rocky Valley—is at Bogong village. Because of the complete lack of contoured maps of the West Kiewa valley, all physiographic studies of this valley were purely qualitative.

The West Kiewa valley is strongly asymmetric, with the steeper slopes on the E. side. Locally, as on the flanks of Mt Fainter, the valley is gorge like, with near vertical walls up to 600 ft high. Dissection on this valley is far more advanced than that observed in other catchments in the area, while the alluviated headwaters, typical of the East Kiewa and Big R., are absent. The Cobungra Gap between the West Kiewa and Cobungra R. is indicative of capture of the West Kiewa headwaters by the Cobungra. Stream gradient averages 1: 20 over almost the full length of the stream, but is steeper in the headwater tributaries. Small alluvial flats are found in the valley floor for the entire length, and, downstream from Young's Gap, these increase in size. The flat at the junction of the West Kiewa and Diamantina is of some interest since it is traversed by a depression, obviously an extremely recent course of the West Kiewa, some 20 ft lower than the present bed. The most probable explanation of this is diversion of the stream by miners who worked this area in the latter half of the last century.

The structural control of this valley is obvious: the valley follows, for the greater part of its length, the mylonite belt of the West Kiewa Thrust, and where the valley leaves this belt, it is on a younger, almost E.-W. structure.

The two main branches of the East Kiewa R. have their sources on the Bogong High Plains. The headwater sections have mature, alluviated valleys, with stream gradients 1: 250. At the knick points the gradient increases to 1: 15. The cross sections of the valleys are asymmetric, with steeper slopes on the E. sides. Flattening of spurs, producing valley in valley structure, is present at elevations 5,000, 4,000 and 3,600 ft. Field study, supplemented by the air photo interpretations, shows a contrast in the stage of development of Pretty Valley with that of Rocky Valley. The latter is more juvenile than the former, particularly downstream from Howman's Gap. Upstream from this gap, both streams have gradient 1: 16, but downstream, Rocky Valley has gradient 1: 10, while Pretty Valley gradient is 1:16 to 1: 20. Slope of the walls of Pretty Valley average 1: 3, whilst those of Rocky Valley have slope of 1: 1·5 to 1: 2.

There is strong evidence that Rocky Valley formerly flowed through Howman's Gap, along the present course of Sassafrass Cr., and had its junction with Pretty Valley just downstream from the Pretty Valley-McKay Cr. junction. Alluvium is found faulted to depths of 110 ft along Sassafrass Cr. Nelse Cr. may formerly have been the main stream, with upper Rocky Valley tributary to it, an idea supported by the generally deeper dissection of this valley than in Rocky Valley. Capture of the main streams by what is now the lower section of Rocky Valley occurred as a result of recent movement on the Sasafrass Creek fault, supplemented by the general warping. Similar capture has occurred near the junction of Spion Kopje Cr. with Rocky Valley.

Below the junction of the two branches, the East Kiewa flows in a youthful valley, with gradient 1: 20, until it crosses the Tawonga Fault, where it reaches grade. As with other streams in the area, the structure has controlled the pattern of this stream. This is particularly so between Junction Dam and Clover Dam where the stream follows the faulted gneiss-granodiorite boundary.

Spion Kopje Cr. is one of the most important tributaries of the East Kiewa. For almost its entire length it occupies the crush zone of the Spion Kopje Fault, leaving this ½ mile upstream from the junction with Rocky Valley, where capture took place. All of the tributaries of this stream have developed on the minor faults of the Spion Kopje system. The stream has a steep gradient ranging between 1: 5 and 1: 1. The valley walls are steep, with slopes between 1: 0·8 and 1: 2.

STRUCTURAL CONTROL OF THE DRAINAGE PATTERN

Although structural control of the drainage pattern is generally indisputable, one catchment, Rocky Valley, was selected for detailed analysis. Attempts to correlate stream and fracture trends showed no clear relationship; however, analysis of variation of trends from E.-W. showed a clear relationship (Table 20).

TABLE 20

Correlation of Stream Trends and Fault Trends

Degrees from E.-W.	x	Faults	Streams	Faults/ Stream y
5	1	25	34	0·74
15	3	15	30	0·50
25	5	12	23	0·52
35	7	4	15	0·27
45	9	3	12	0·25
55	11	8	22	0·36
65	13	4	17	0·25
75	15	4	30	0·13
85	17	9	37	0·24

Correlation coefficient $r_{xy} = 0{\cdot}8$.

In this catchment, faults appear to have influenced the development of streams with an E.-W. trend more than that of streams with other trends. When this technique was applied to the whole of the area, no statistical correlation was found, so that the tentative conclusion reached for Rocky Valley is not generally applicable, a finding already established in the field.

As stated earlier, the general fault warping has exerted a considerable influence on the streams. On the SE. of the axis, capture has been by E.-flowing streams, and on the NW. side of the axis, by W.-flowing streams. Capture in both cases was due to increase in stream gradient with the warping. This is clear evidence that the fault movements, responsible for the warping, have continued late in the history of the area.

The relationship between structure and drainage pattern in the Kiewa area is a restricted example of the more general relationship which exists throughout NE. Victoria (Thomas 1949, Hills 1955b). Crohn ascribed the captures in the region to an earlier cycle of erosion, and concluded that the stream pattern was antecedent to the recent tectonic movements. It is true that the streams have generally developed on ancient faults, but the captures have clearly taken place during the present cycle. The movements of the warping began about the time of extrusion of the Older Basalts, and periods of still stand, indicated by the flattening of spurs at elevations 6,000; 5,800; 5,000; 4,200; and 3,600 ft, were frequent. With these repeated interruptions to the cycle, the physiographic development of the area would be expected to show considerable complexity, and there is no simple explanation for all of the features observed.

STRUCTURE AND ECONOMIC GEOLOGY

Very few ore bodies have been recorded in the Kiewa area. Gold mines have operated at Hotham Heights (Kenny 1941), Tawonga (Beavis 1949), and Glen Wills (Crohn 1958). Crohn reported torbenite from Glen Wills, while small crystals of this mineral were found by tunnelers in the alluvium of the Kiewa R. Although tantalite found by the author on Mt Bogong was associated with a pegmatite dyke, all other ore bodies in the area are associated with faults.

During the present work, the main economic interest was in the influence of geology in the design and construction of the Kiewa Hydroelectric Project. Although a vast amount of work was done in this field it is possible here only to summarize the main findings.

JOINTS

In engineering excavations, the majority of groundwater discharges occurred along joints. Some discharges were associated with the crush zones of faults, but these were comparatively rare. A certain selectivity was noted, only some joints discharging groundwater; these were not restricted to any one set. The numerous shafts sunk in the area provided ideal conditions for the study of groundwater flow in jointed rocks, and the results suggested that flow under these conditions was similar to that through a porous medium, the joints having, en masse, the role of pores.

Leakage from unlined pressure tunnels, and around and beneath dams was restricted mainly to joints. Joints, however, were important more in the way they controlled stability of excavations. Portal works for the No. 4 Head Race Tunnel involved benching on the nose of a spur in jointed gneiss. The excavation affected the stability conditions of the spur, and there was a tendency to failure by sliding along joint planes. At Clover Dam, on the W. abutment, the sheeting tended to control the stability of the slopes with respect to sliding, and movement along sheeting tended to induce sliding along tectonic joints. At No. 4 Underground Power Station, the long axis of the station was parallel to one set of major tectonic joints. During construction, one wall of the station failed along one of the joints. At depth, the tectonic joints were generally 'tight', but they normally opened as an expression of the redistribution of stresses which followed excavation.

FAULTS

In engineering construction, the significance of faults depended on the width of the crush zone, the material comprising the crush zone, and the attitude of the faults in relation to the excavation. Crush zones of gouge and breccia were responsible for difficult excavation, whilst mylonites created no problems of any magnitude. The importance of orientation of the faults is illustrated by the 6 inch fault which formed one wall of the upstream section of the No. 4 Tail Race Tunnel, and traversed the pillars between the draft tubes of the power station. This fault was responsible for failure both of the wall of the tunnel and of the pillars. Worst conditions existed when the faults were parallel to the long axis of the excavation.

Faults were frequently met in dam foundations. These had inferior foundation properties, and special design was required. At the site of the No. 1 Underground Power Station the soil developed on a very wide crush zone proved to be very unstable with respect to sliding, and it was impossible to construct permanent structures on the zone. No faults are known to be active in the Kiewa area, but it is not improbable that movement could occur on some of the younger structures.

The intimate association of the lamprophyre dykes with faults led to engineers regarding the dykes as troublesome. In fact, with the rare exception of rapidly weathering dykes, these structures, in themselves, created no problems in construction, unless they were sheared. Where the dykes were deeply weathered, excavation down to fresh rock was often desirable, but unless the dykes were thick, this excavation was not carried out.

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Explanation of Plates

Plate XXXIX

(Ordinary Light)

Fig. 1—Knotted schist, Mt Bogong.
Fig. 2—Knotted schist, Mt Nelse.
Fig. 3—Low grade schist, Cobungra Gap.
Fig. 4—Permeation gneiss at contact with granodiorite, Spion Kopje.
Fig. 5—Gneissic granodiorite, Pretty Valley.
Fig. 6—Andalusite rock, contact of knotted schist with granodiorite, Mt Nelse.

Plate XL

Fig. 1—Leaf beds, Bundarrah R.
Fig. 2—Basalt at Basalt Hill.
Fig. 3—Exposure of Bogong Fault, East Kiewa R.
Fig. 4—Fold in schist, Mt Nelse.
Fig. 5—Shear in Upper Ordovician sediments near West Kiewa Thrust, Mt Hotham.

PLATE XLI

Fig. 1—Lamprophyre dykes intruded along joints in granodiorite, with later joints traversing both rocks, Falls Cr.
Fig. 2—Lamprophyre dykes intruded along joint in granodiorite, Rocky Valley Dam.
Fig. 3—Flat shear in granodionite, Windy Gap.
Fig. 4—Weathering on joints in granodiorite, Rocky Valley.

PLATE XLII

Fig. 1—Strike ridges in Upper Ordovician sediments. with Mt Buffalo in distance.
Fig. 2—The basalts of the Bogong High Plains, from Niggerheads.
Fig. 3—Spion Kopje Cr.. developed on Spion Kopje Fault.
Fig. 4—A typical High Plains valley—Pretty Valley, looking towards the knick point.